[*From a photograph by Elliott and Fry*

DR. JOHN HOPKINSON, F.R.S.

ELECTRIC MACHINE DESIGN

BEING A REVISED AND ENLARGED EDITION OF

"ELECTRIC GENERATORS"

BY

HORACE FIELD PARSHALL

AND

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THIS BOOK IS DEDICATED

TO

THE MEMORY OF

DR. JOHN HOPKINSON, F.R.S.

THE FOUNDER OF THE

"SCIENCE OF DYNAMO DESIGN"

TABLE OF CONTENTS

PART I.—CONTINUOUS-CURRENT GENERATORS

PART IV.—ALTERNATORS

LIST OF ILLUSTRATIONS

ELECTRIC TRACTION MOTORS

ROTARY CONVERTERS.

ALTERNATORS.

LIST OF TABLES

CONTINUOUS-CURRENT GENERATORS

ELECTRIC TRACTION MOTORS

ROTARY CONVERTERS

PREFACE

THE present volume is a revision and an enlargement of our book entitled "Electric Generators." That volume was an amplification of the notes of a series of lectures given, first by Mr. Parshall and continued by Mr. Hobart, at the Massachusetts Institute of Technology, some years ago. Concerning that volume we made the following observations in the Preface :—

"The original notes met with so cordial an appreciation from Lord Kelvin, the late Dr. John Hopkinson, and others, that the Authors determined to follow out a suggestion made, and publish a book on the design of Electric Generators. The work of revising the original notes gradually led to the bringing together of an amount of material several times larger than was at first intended, and a comprehensive treatment of the subject prevented reducing this amount. In this form the work appeared as a series of articles in *Engineering* during the years 1898 and 1899. The interest taken in the series leads us to believe that, despite the present large number of books on the theory of commutating machines, the extended practical experience of the Authors, covering the period during which most of the modern types of machines have been developed, justifies the publication of the present treatise.

"In dealing with the practice of designing, three sub-divisions can be finally made :—

"The first may be taken as relating to the design of the magnetic circuit. The classical papers of Doctors John and Edward Hopkinson

have dealt with this subject so completely that there remains but little to be written; and this relates chiefly to the nature and properties of the different qualities of iron and steel which may be used in the construction of the magnetic circuit.

"The second sub-division considers the phenomena of commutation and the study of dimensions, with a view to securing the greatest output without diminishing the efficiency. The theory of commutation has become better understood since electrical engineers began to deal with alternating currents and to understand the effects of self-induction. However, owing to the number of variables affecting the final results, data obtained in practice must be the basis for the preparation of new designs. In this work will be found a statement of such results, and numerical values experimentally obtained from representative commutating machines. One familiar with the theory of commutation can, with comparative certainty, from the values and dimensions given, design machines with satisfactory commutating properties.

"The third sub-division relates to what we have termed the 'Thermal Limit of Output': that is, the maximum output with safe heating. It can be fairly said that while the theory of all the losses in a commutating dynamo is understood, yet, with the exception of the C^2R losses, it is still a matter of practical experience to determine what relation the actual losses bear to what may be termed the predicted losses. It is invariably found that the iron losses are in excess of those which may be predicted from the tests made upon the material before construction. The hysteresis loss in the armature core is generally found to be greater, owing to the mechanical processes to which the material in the core has to be subjected during the process of construction. Owing, probably, in a large measure to a species of side magnetisation, the eddy-current loss is found to be greater than is indicated by calculations based upon the assumption of a distribution of magnetic lines parallel to the plane of the laminations. If the armature conductors are solid, the losses therein by Foucault currents may often be considerable, even in projection-type armatures, especially when the projections are

run at high densities. Under load losses, not including friction, there have to be considered the Foucault current loss in the conductors due to distortion, and the increased loss in the armature projections from hysteresis and eddy currents likewise due thereto. There is also the loss brought about by the reversal of the current in the armature coil under commutation. It is apparent, therefore, considering that each of these variables is dependent upon the form of design, the material used, and the processes of construction, that only an approximate estimate as to the total loss can be made from the theoretical consideration of the constants. We believe, therefore, that these considerations will justify the length with which we have dealt with the thermal limit of output."

These observations largely apply to the present volume. The title "Electric Generators" was adopted when only that subject was dealt with. As our work extended, we included other classes of machines which we were from time to time called upon to design or investigate, so that the title "Electric Generators" was no longer fairly descriptive of the book. The book is intended as a work of reference for designers, and its application has been almost entirely in this field. A suggestion was made that the title "Electric Generators" was misleading as to the scope of the work comprehended; and after discussing the question with a number of engineers who have made liberal use of "Electric Generators," we decided upon the present title, viz., "Electric Machine Design," which will, we trust, more fitly describe the nature of the subjects dealt with.

To the original section, on Continuous Current Generators, many additions have been made, including designs of machines that have proved in practice to be exceptionally good. In "Electric Generators" certain designs not of the greatest excellence were included as illustrative of certain features; in the present edition we have made it as far as possible a principle to include only particulars of machines that have proved in practice to represent an advanced state of the art of Electric Machine Design.

The designs in general are to illustrate the different phases of dynamo construction, and not to furnish working models for manufacture. No well-advised engineer should blindly follow another's designs. A complete description of a machine, together with the final test results, is of great use to a designer, but only as a basis from which to work. Few machines have been built and tested without revealing, on careful analysis, the direction in which further improvements were practicable. The manufacturer who has just standardised a design cannot sacrifice the developmental costs and proceed at once with the ultra-refinements of an improved design, but he will frequently have done so long before any published description is available, and the manufacturer who blindly copies such a published description may, on completion of a machine, find he has only reproduced a more-or-less obsolete type. While indiscriminate copying is generally accompanied with unsatisfactory results, a judicious reference to the constants of successful designs points the way for further progress. It is the object of this work to furnish the constants and to formulate the general principles for the systematic designing of electrical machines.

The progress made in the design of commutating machines has been along the lines indicated in our original work, and shows that our theories were valid.

Perfect commutation may be said to take place when, with the same conditions as to current density, dimensions and materials, the heating and wearing of a commutator is the same as that of a simple collector ring. Beyond certain limits as to current density and friction, collector rings roughen and wear away; hence in modern practice steel and bronze collectors with carbon brushes are employed. The fundamental conditions in both commutator and collector are the same, and in first-class commutating machines commutation does not introduce widely different results: that is to say, the current generated in a given machine should not produce widely different results as to heating and wearing of the commutator and brushes, from those produced by

an equal current sent through the same machine with its armature windings short-circuited.

Pronounced thermal effects from commutation do not occur in normal practice. The limiting conditions in practice relate to the reactance voltage of commutation, and the stability of field distribution of a commutated circuit under varying armature reaction in its relation to resistance. The effect of resistance is to increase the rate at which the current can be reversed, thereby diminishing the maximum field strength required for reversal, and lessening the deleterious currents when the reversing field is of excessive strength. The contact resistance cannot be varied beyond certain limits to effect commutation. Should these limits be exceeded, the current could not be collected, without excessive wear of the commutator or collector. The disintegration of the brushes may be caused either by friction and uneven wearing, or by excessive current density of the collected or commutated currents. This uneven wearing causes the formation of minute arcs, that eventually destroy the surface of the commutator, and lead to excessive sparking. Defective conductivity and commutation may one and both present themselves in the same machine simultaneously or separately under different conditions of working.

Certainty of results in practice can only be obtained by adjusting the inductance and distortion to bear a proper relation to the collector system. An investigation of one element is of no value unless connected with all the other elements. The whole process of designing is that of balancing one condition against another; and in the matter of commutating machines this balancing is confined by commercial necessities to comparatively narrow limits. A microscopical study of the contact surfaces of brushes often furnishes evidence of action, both mechanical and electrical, not otherwise immediately observable.

A considerable proportion of the treatise is devoted to continuous-current generators. The design of this class of machinery involves every problem entering into the design of any class of electrical machinery, and an engineer with reasonable mathematical training

properly grounded in this class of machine, should experience no difficulty in dealing with any other class of machine. The calculation of leakage, reluctance, and reactance is as essential to the proper designing of continuous-current generators as to alternating current machines; and owing to the high frequency of commutation a closer mathematical analysis is necessary in this case than in the design of any class of alternating-current machines.

Our treatment of alternator design may be described as synthetic, since in practice broad mathematic treatment is too cumbersome in the balancing process which is the substance of all designing work.

Certain sections of the book admit of very considerable extension. The size of the present volume, however, together with our general scheme of dealing only with machinery, more or less standardised, have been the limiting factors in the treatment of the different subjects.

H. F. P.
H. M. H.

PART I

CONTINUOUS-CURRENT GENERATORS

ELECTRIC GENERATORS

MATERIALS

A CONSIDERABLE variety of materials enters into the construction of dynamo electric apparatus, and it is essential that the grades used shall conform to rather exacting requirements, both as regards electric and magnetic conductivity as well as with respect to their mechanical properties.

TESTING OF MATERIALS

The metallic compounds employed in the magnetic and conducting circuits must be of definite chemical composition. The effect of slight differences in the chemical composition is often considerable; for instance, the addition of 3 per cent. of aluminium reduces the conductivity of copper in the ratio of 100 to 18.[1] Again, the magnetic permeability of steel containing 12 per cent. of manganese is scarcely greater than unity.

The mechanical treatment during various stages of the production also in many cases exerts a preponderating influence upon the final result. Thus, sheet iron frequently has over twice as great a hysteresis loss when unannealed as it has after annealing from a high temperature. Cast copper having almost the same chemical analysis as drawn copper, has only 50 per cent. of its conductivity. Pressure exerts a great influence upon the magnetic properties of sheet iron.[2] Sheet iron of certain compositions, when subjected for a few weeks, even to such a moderate temperature as 60 deg. Cent., becomes several times as poor for magnetic purposes as before subjection to this temperature.[3]

It thus becomes desirable to subject to chemical, physical, and electromagnetic, tests samples from every lot of material intended for use in the

[1] *Electrician*, July 3rd, 1896. Dewar and Fleming. [2] See page 36, and Figs. 37 and 38.
[3] See pages 33 to 35, and Figs. 30 to 36.

construction of dynamo-electric apparatus. This being the case, the importance of practical shop methods, in order that such tests may be quickly and accurately made, becomes apparent.

Conductivity Tests

The methods used in conductivity tests are those described in text-books devoted to the subject.[1] It will suffice to call attention to the investigations made by Professors Dewar and Fleming,[2] the results of which show that materials in a state of great purity have considerably higher conductivity than was attributed to them as the results of Matthiessen's experiments. Manufactured copper wire is now often obtained with a conductivity exceeding Matthiessen's standard for pure copper.

Copper wire, drawn to small diameters, is apt to be of inferior conductivity, due to the admixture of impurities to lessen the difficulties of manufacture. It consequently becomes especially desirable to test its conductivity in order to guard against too low a value.

The electrical conductivity of German silver and other high resistance alloys varies to such an extent that tests on each lot are imperative, if anything like accurate results are required.[3]

Permeability Tests

Considerable care and judgment are necessary in testing the magnetic properties of materials, even with the most recent improvements in apparatus and methods. Nevertheless, the extreme variability in the magnetic properties, resulting from slight variations in chemical composition and physical treatment, render such tests indispensable in order to obtain uniformly good quality in the material employed. Various methods have been proposed with a view to simplifying permeability tests, but the most accurate method, although also the most laborious, is that in which the sample is in the form of a ring uniformly wound with primary and secondary coils, the former permitting of the application of any desired

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[1] Among the more useful books on the subject of electrical measurements are Professor S. W. Holman's *Physical Laboratory Notes* (Massachusetts Institute of Technology), and Professor Fleming's *Electrical Laboratory Notes and Forms*.

[2] *Electrician*, July 3rd, 1896.

[3] A table of the properties of various conducting materials is given later in this volume.

magnetomotive force, and the latter being for the purpose of determining, by means of the swing of the needle of a ballistic galvanometer, the corresponding magnetic flux induced in the sample.

Description of Test of Iron Sample by Ring Method with Ballistic Galvanometer

The calibrating coil consisted of a solenoid, 80 centimetres long, uniformly wound with an exciting coil of 800 turns. Therefore, there were 10 turns per centimetre of length. The mean cross-section of exciting coil was 18.0 square centimetres. The exploring coil consisted of 100 turns midway along the solenoid. Reversing a current of 2.00 amperes in the exciting coil gave a deflection of 35.5 deg. on the scale of the ballistic galvanometer when there were 150 ohms resistance in the entire secondary circuit, consisting of 12.0 ohms in the ballistic galvanometer coils, 5.0 ohms in the exploring coil, and 133 ohms in external resistance.

$$H = \frac{4 \pi n C}{10 l}; \quad \frac{n}{l} = 10.0; \quad C = 2.00;$$

$$\therefore H = \frac{4 \pi}{10} \times 10.0 \times 2.00 = 25.1,$$

i.e., 2.00 amperes in the exciting coil set up 25.1 lines in each square centimetre at the middle section of the solenoid; therefore 18.0 × 25.1 = 452 total C G S. lines. But these were linked with the 100 turns of the exploring coil, and therefore were equivalent to 45,200 lines linked with the circuit. Reversing 45,200 lines was equivalent in its effect upon the ballistic galvanometer to creating 90,400 lines, which latter number, consequently, corresponds to a deflection of 35.5 deg. on the ballistic galvanometer with 150 ohms in circuit. Defining K, the constant of the ballistic galvanometer, to be the lines per degree deflection with 100 ohms in circuit, we obtain

$$K = \frac{90400}{35.5 \times 1.50} = 1690 \text{ lines.}$$

The cast-steel sample consisted of a ring of 1.10 square centimetres cross-section, and of 30 centimetres mean circumference, and it was wound with an exciting coil of 450 turns, and with an exploring coil of 50 turns. With 2.00 amperes exciting current,

$$H = \frac{4 \pi}{10} \times \frac{450}{30} \times 2.00 = 37.7.$$

Reversing 2.00 amperes in the exciting coil gave a deflection of 40 deg. with 2,400 ohms total resistance of secondary circuit. Then with 100 ohms instead of 2,400 ohms, with one turn in the exploring coil instead of 50 turns, and simply creating the flux instead of reversing it, there would have been obtained a deflection of

$$\frac{2400}{100} \times \frac{1}{50} \times \frac{1}{2} \times 40 = 9.60 \text{ deg.};$$

consequently the flux reversed in the sample was

$$9.60 \times 1{,}690 = 16{,}200 \text{ lines.}$$

And as the cross-section of the ring was 1.10 square centimetres, the density was

$$16{,}200 \div 1.10 = 14{,}700 \text{ lines per square centimetre.}$$

Therefore the result of this observation was

$$H = 37.7; \qquad B = 14{,}700; \qquad \mu = 390.$$

But in practice[1] this should be reduced to ampere turns per inch of length, and lines per square inch;

Ampere-turns per inch of length $= 2\,H = 75.4$.
Density in lines per square inch $= 6.45 \times 14{,}700 = 95{,}000$.

This would generally be written 95.0 kilolines. Similarly, fluxes of still greater magnitude are generally expressed in megalines. For instance,

12.7 megalines = 12,700,000 C G S lines.

[1] Although mixed systems of units are admittedly inferior to the metric system, present shop practice requires their use. It is, therefore, necessary to readily convert the absolute B H curves into others expressed in terms of the units employed in practice. In absolute measure, iron saturation curves are plotted, in which the ordinates B represent the density in terms of the number of C G S lines per square centimetre, the abscissæ denoting the magnetomotive force H. B/H equals μ, the permeability. In the curves used in practice the ordinates should equal the number of lines per square inch. They are, therefore, equal to 6.45 B. The abscissæ should equal the number of ampere-turns per inch of length. Letting turns $= n$, and amperes $=$ C, we have—

$$H = \frac{4\,\pi\,n\,C}{10\,l}, \quad l \text{ being expressed in centimetres.}$$

$$\therefore \text{Ampere-turns per centimetre of length} = \frac{10\,H}{4\,\pi},$$

$$\text{Ampere-turns per inch of length} = \frac{2.54 \times 10\,H}{4\,\pi},$$

$$\text{Ampere-turns per inch of length} = 2.02\,H.$$

Therefore ampere-turns per inch of length are approximately equal to 2 H.

Other Permeability Testing Methods

The bar and yoke method, devised by Dr. Hopkinson, permits of the use of a rod-shaped sample, this being more convenient than a ring, in that the latter requires that each sample be separately wound, whereas in the rod and yoke method the same magnetising and exploring coils may be used for all samples. However, the ring method is more absolute, and affords much less chance for error than is the case with other methods, where the sources of error must either be reduced to negligible proportions, which is seldom practicable, or corrected for. Descriptions of the Hopkinson apparatus are to be found in text-books on electro-magnetism,[1] and the calculation of the results would be along lines closely similar to those of the example already given for the case of a ring sample.

Methods of Measuring Permeability not Requiring Ballistic Galvanometer

There have been a number of arrangements devised for the purpose of making permeability measurements without the use of the ballistic galvanometer, and of doing away with the generally considerable trouble attending its use, as well as simplifying the calculations.

Those in which the piece to be tested is compared to a standard of known permeability, have proved to be the most successful. The Eickemeyer bridge[2] is a well-known example, but it is rather untrustworthy, particularly when there is a great difference between the standard and the test-piece.

A method of accomplishing this, which has been used extensively with very good results, has been devised by Mr. Frank Holden. It is described by him in an article entitled "A Method of Determining Induction and Hysteresis Curves" in the *Electrical World* for December 15th, 1894. The principle has been embodied in a commercial apparatus constructed by Mr. Holden in 1895,[3] and also in a similar instrument exhibited by Professor Ewing before the Royal Society in 1896.[4]

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[1] Also J. Hopkinson, *Phil. Trans.*, page 455, 1885.

[2] *Electrical Engineer*, New York, March 25th, 1891.

[3] "An Apparatus for Determining Induction and Hysteresis Curves," *Electrical World*, June 27th, 1896.

[4] "The Magnetic Testing of Iron and Steel," *Proceedings*, Institution of Civil Engineers, May, 1896.

Holden's method consists essentially of an arrangement in which two bars are wound uniformly over equal lengths, and joined at their ends by two blocks of soft iron into which they fit. The rods are parallel, and about as close together as the windings permit. In practice it has been found most convenient to use rods of about .25 in. in diameter, and about 7 in. long. Over the middle portion of this arrangement is placed a magnetometer, not necessarily a very sensitive one, with its needle tending to lie at right angles to the length of the two bars, the influence of the bars tending to set it at right angles to this position. Means are

FIG. 1. HOLDEN'S PERMEABILITY BRIDGE

provided for reversing simultaneously, and for measuring, each of the magnetising currents, which pass in such directions that the north end of one rod and the south end of the other, are in the same terminal block. It is evident that whenever the magnetometer shows no effect from the bars, the fluxes in them must be equal, for if not equal there would be a leakage from one terminal block to the other through the air, and this would effect the magnetometer. This balanced condition is brought about by varying the current in one or both of the bars, and reversing between each variation to get rid of the effects of residual magnetism.

For each bar

$$H = \frac{4 \pi n C}{10 l},$$

where

n = number of turns,
C = current in amperes,
l = distance between blocks in centimetres.

As the same magnetising coils may always be used, and as the blocks may be arranged at a fixed distance apart,

$$\frac{4 \pi n}{10 l} = K$$

and

$$H = K C.$$

The B H curve of the standard must have been previously determined, and when the above-described balance has been produced and the magnetomotive force of the standard calculated, the value of B is at once found by reference to the characteristics of the standard. If the two bars are of the same cross-section, this gives directly the B in the test-piece, and H is calculated as described. The method furnishes a means of making very accurate comparisons, the whole test is quickly done, and the chances of error are minimised by the simplicity of the process. The magnetometer for use with bars of the size described need not be more delicate than a good pocket compass. Although two pieces of quite opposite extremes of permeability may be thus compared, yet it takes less care in manipulating, if two standards are at hand, one of cast iron and one of wrought iron or cast steel, and the standard of quality most like that of the test-piece should be used.

Sheet iron may be tested in the same way, if it is cut in strips about .5 in. wide and 7 in. long. This will require the use of specially-shaped blocks, capable of making good contact with the end of the bundle of strips which may be about .25 in. thick. In general the cross-sections of the test-piece and standard in this case will not be equal, but this is easily accounted for, since the induction values are inversely as the cross-sections when the total fluxes are equal. In Figs. 1 and 2 are shown both the Holden and the Ewing permeability bridges.

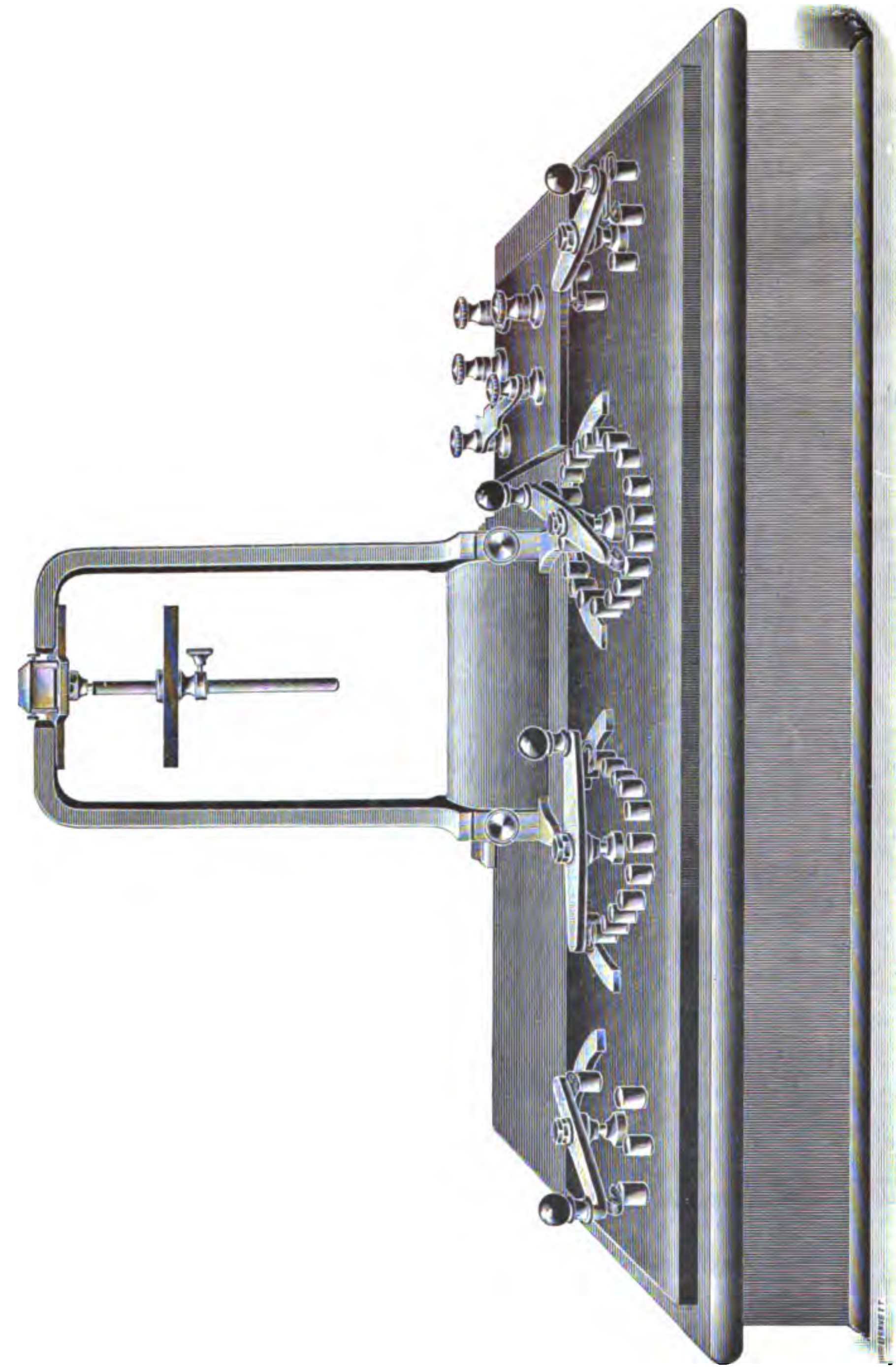

FIG. 2. EWING'S PERMEABILITY BRIDGE

Determinaton of Hysteresis Loss

The step-by-step method of determining the hysteresis loss, by carrying a sample through a complete cycle, has been used for some years past, and is employed to a great extent at the present time. Such a test is made with a ring-shaped sample, and consists in varying by steps the magnetomotive force of the primary coil, and noting by the deflection of a ballistic galvanometer the corresponding changes in the flux. From the results a complete cycle curve, such as is shown in Fig 3, may be plotted. If this curve is plotted with ordinates equal to B (C G S lines per square centi-

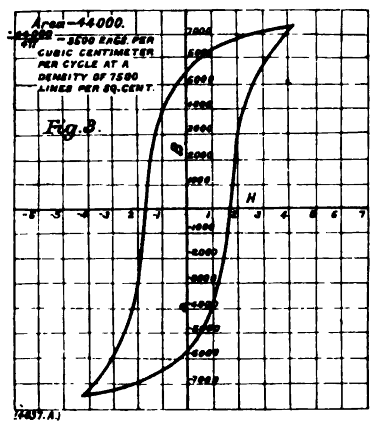

Fig. 3. Cyclic Curve for Sheet Iron

metre), and with abscissæ equal to H, $\left(\frac{4\ \pi\ n\ C}{10\ l}\right)$, its area divided by $4\ \pi$ (conveniently determined by means of a planimeter), will be equal to the hysteresis loss of one complete cycle, expressed in ergs per cubic centimetre[1]; but in subsequent calculations of commercial apparatus it is more convenient to have the results in terms of the watts per pound of material per cycle per second. The relation between the two expressions may be derived as follows:

Conversion of Units

Ergs per cubic centimetre per cycle

$$= \frac{\text{Area complete cyclic curve}}{4\ \pi}$$

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[1] Fleming, *Alternate Current Transformer*, second edition, page 62.

C

Watts per cubic centimetre at one cycle per second

$$= \frac{\text{Area}}{4\pi \times 10^7}$$

Watts per cubic inch at one cycle per second

$$= \frac{\text{Area} \times 16.4}{4\pi \times 10.^7}$$

Watts per pound at one cycle per second

$$= \frac{\text{Area} \times 16.4}{4\pi \times 10^7 \times .282}$$

(One cubic inch of sheet iron weighing .282 lb.)

$\therefore$ Watts per pound at one cycle per second = .0000058 × ergs per cubic centimetre per cycle.

Hysteresis Losses in Alternating and Rotating Fields

Hysteresis loss in iron may be produced in two ways: one when the magnetising force acting upon the iron, and consequently the magnetisation, passes through a zero value in changing from positive to negative, and the other when the magnetising force, and consequently the magnetisation, remains constant in value, but varies in direction. The former condition holds in the core of a transformer, and the latter in certain other types of apparatus. The resultant hysteresis loss in the two cases cannot be assumed to be necessarily the same. Bailey has found[1] that the rotating field produces for low inductions, a hysteresis loss greater than that of the alternating field, but that at an induction of about 100 kilolines per square inch, the hysteresis loss reaches a sharply defined maximum, and rapidly diminishes on further magnetisation, until, at an induction of about 130 kilolines per square inch, it becomes very small with every indication of disappearing altogether. This result has been verified by other experimenters, and it is quite in accord with the molecular theory of magnetism, from which, in fact, it was predicted. In the case of the alternating field, when the magnetism is pressed beyond a certain limit, the hysteresis loss becomes, and remains, constant in value, but does not decrease as in the

[1] See paper on "The Hysteresis of Iron in a Rotating Magnetic Field," read before the Royal Society, June 4th, 1896. See also an article in the *Electrician* of October 2nd, 1896, on "Magnetic Hysteresis in a Rotating Field," by R. Beattie and R. C. Clinker. Also *Electrician*, August 31st, 1894, F. G. Bailey. Also *Wied. Ann.*, No. 9, 1898, Niethammer. Also *Phil. Mag.*, June, 1901, R. Beattie. Also *Electtricità*, Milan, September 28th, October 5th, October 19th, 1901. Also *Elektrotechn. Zeitschr.*, February 13th, 1902, "Hysteresis in a Rotating Field," by R. Heicke. Also *Elektrotechn. Zeitschr.*, May 15th, 1902, "Hysteresis in a Rotating Field," by M. Schenkel.

case of the rotating magnetisation. Hence, as far as hysteresis loss is concerned, it might sometimes be advantageous to work with as high an induction in certain types of electro-dynamic apparatus as possible, if it can be pressed above that point where the hysteresis loss commences to decrease; but in the case of transformers little advantage would be derived from high density on the score of hysteresis loss, as the density, except at very low cycles, cannot be economically carried up to that value at which the hysteresis loss is said to become constant.

FIG. 4. SAMPLE FOR USE IN HOLDEN'S HYSTERESIS TESTER

METHODS OF MEASURING HYSTERESIS LOSS WITHOUT THE BALLISTIC GALVANOMETER

To avoid the great labour and expenditure of time involved in hysteresis tests by the step-by-step method with the ballistic galvanometer, there have been many attempts made to arrive at the result in a more direct manner. The only type of apparatus that seems to have attained commercial success measures the energy employed either in rotating the test-piece in a magnetic field, or in rotating the magnetic field in which the test-piece is placed.

The Holden hysteresis tester[1] is the earliest of these instruments, and

[1] "Some Work on Magnetic Hysteresis," *Electrical World*, June 15th, 1895.

appears to be the most satisfactory. It measures the loss in sheet-iron rings when placed between the poles of a rotating magnet, and enables the loss to be thoroughly analysed. The sheet-iron rings are just such as would be used in the ordinary ballistic galvanometer test (Fig. 4, page 11).

The rings are held concentric with a vertical pivoted shaft, around which revolves co-axially an electro-magnet which magnetises the rings. The sample rings are built up into a cylindrical pile about ½ in. high.

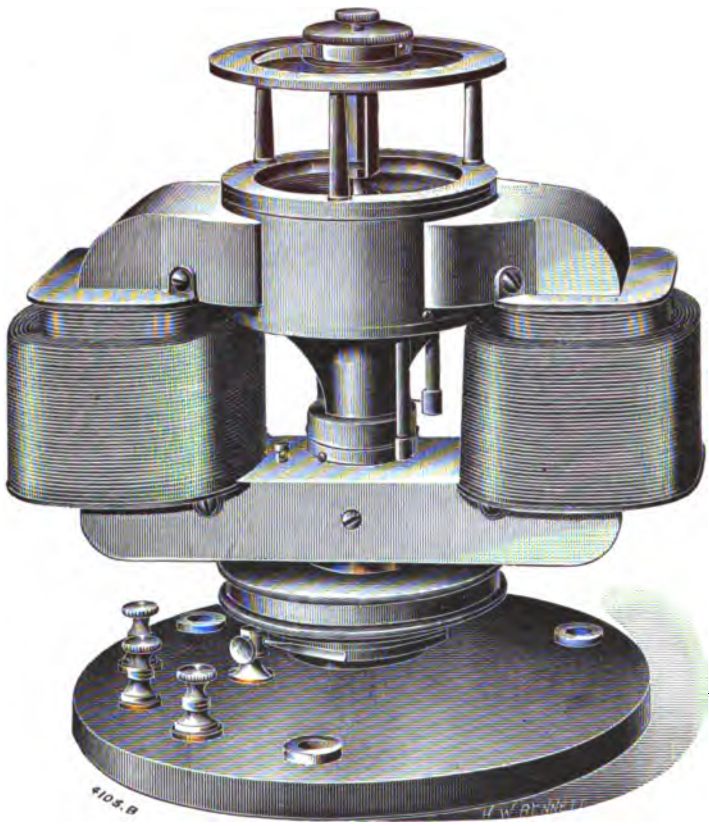

Fig. 5. Holden's Hysteresis Testing Apparatus

Surrounding but not touching the sample to be tested is a coil of insulated wire, the terminals of which lead to a commutator revolving with the magnet. The alternating electromotive force of the coil is thus rectified, and measured by a Weston Voltmeter. Knowing the cross-section of the sample, the number of turns in the coil, the angular velocity of the magnet, and the constants of the voltmeter, the induction corresponding to a certain deflection of the voltmeter, can be calculated in an obvious manner.[1]

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[1] For electromotive force calculations, see another page in this volume.

The force tending to rotate the rings is opposed by means of a helical spring surrounding the shaft and attached to it at one end. The other end is fixed to a torsion head, with a pointer moving over a scale. The loss per cycle is proportional to the deflection required to bring the rings to their zero position, and is readily calculated from the constant of the spring.

By varying the angular velocity of the magnet, a few observations give data by which the effect of eddy currents may be allowed for and the residual hysteresis loss determined ; or, by running at a low speed, the eddy current loss becomes so small as to be practically negligible, and readings taken under these conditions are, for all commercial purposes, the only ones necessary. A test sample with wire coil is shown in Fig. 4, whilst the complete apparatus may be seen in Fig. 5, page 12.

A modification (Fig. 6) of this instrument does away with the adjust-

FIG. 6. MODIFICATION OF HOLDEN'S HYSTERESIS TESTING APPARATUS

ment of the magnetising current and the separate determination of the induction for different tests. In this case the electro-magnet is modified into two of much greater length, and of a cross-section of about one-third that of the sample lot of rings. The air gap is made as small as practicable, so that there is very little leakage. A very high magnetomotive force is applied to the electro-magnets, so that the flux in them changes only very slightly with considerable corresponding variation in the current. With any such variation from the average as is likely to occur in the rings on account of varying permeability, the total flux through them will be nearly constant, with the magnetisation furnished in this manner. The sample rotates in opposition to a spiral spring, and the angle of rotation is proportional to the hysteresis loss. In general a correction has to be applied for volume and cross-section, as the rings do not, owing to variations in the thickness of the sheets, make piles of the same height. The

magnets are rotated slowly by giving them an impulse by hand, and the reading is made when a steady deflection is obtained.

Ewing's Hysteresis Tester

In Professor Ewing's apparatus[1] the test sample is made up of about seven pieces of sheet iron $\frac{5}{8}$ in. wide and 3 in. long. These are rotated

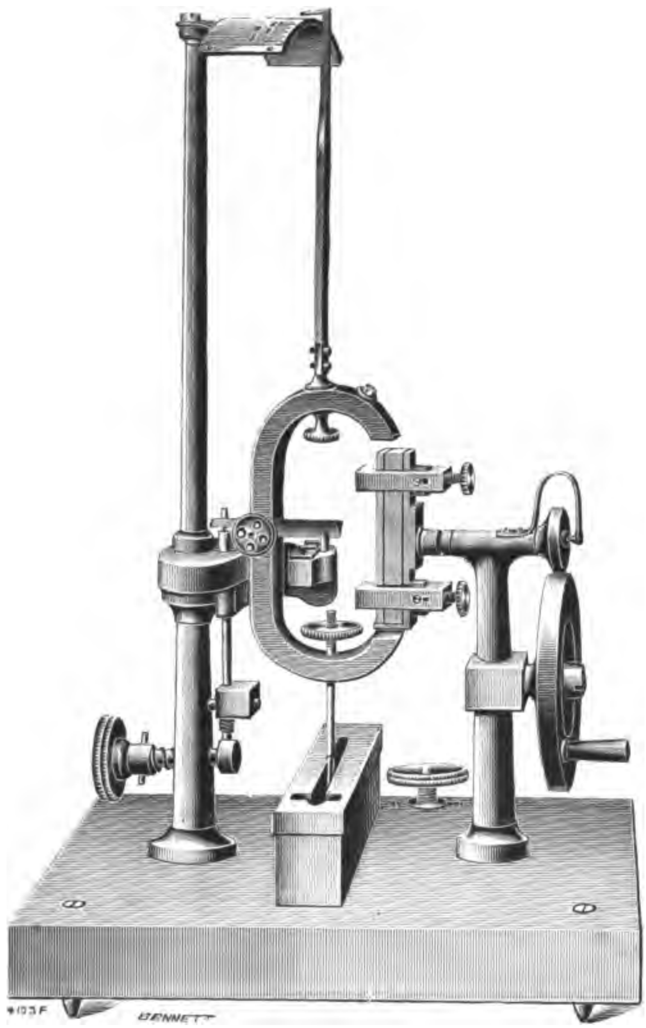

Fig. 7. Ewing's Hysteresis Testing Device

between the poles of a permanent magnet mounted on knife-edges. The magnet carries a pointer which moves over a scale. Two standards of known hysteresis properties are used for reference. The deflections corres-

[1] *Electrician*, April 26th, 1895.

ponding to these samples are plotted as a function of their hysteresis losses, and a line joining the two points thus found is referred to in the subsequent tests, this line showing the relation existing between deflections and hysteresis loss. The deflections are practically the same, with a great variation in the thickness of the pile of test-pieces, so that no correction has to be made for such variation. It has, among other advantages, that of using easily prepared samples. The apparatus is shown in Fig. 7.

A fair specification for the hysteresis loss is that samples cut at random from various sheets, shall, when tested by the Ewing Hysteresis Tester, not show on the average a hysteresis loss of more than 0.50 watts per pound when reduced to 100 cycles per second, and 24,000 lines per square inch. This reduction is readily made by comparison with the calibrating samples accompanying the instrument.

Modern practice, however, as regards hysteresis tests tends towards the simple measurement by means of an ordinary commercial wattmeter, of the watts lost in a given weight of laminations of specified dimensions, cut from plates selected at random from a car load, and built up into a small bundle and provided with a suitable winding. At some standard periodicity, the voltage at the terminals of the winding is adjusted at such a value as to correspond to a reference density—say, 24,000 lines per square inch—and the plates are accepted or rejected according as the core loss is less or greater than the specified value.

The Testing of Whole Sheets of Iron

Sheets as received from the iron manufacturer are tested by the firm of Siemens and Halske, of Vienna, by sliding them by suitable means into a large cylindrical drum, so that they constitute a ring of about a metre diameter, with a section measuring a metre or more in one direction, by a couple of millimetres or so in the other. The frame is provided with a permanent annular winding enclosing the sheets. From four to six sheets are preferably tested together. Various precautionary details must be observed in arranging an interlapped closing of the magnetic circuit, in insulating the sheets from one another laterally, and especially in avoiding short circuits through their touching at their edges. Some of these precautions have been found superfluous in commercial testing.

The method is so convenient that a few sheets from a given shipment may be unloaded and tested, in order to determine whether the entire shipment shall be accepted.

An early form of this apparatus was described in the *Elektrotechnische Zeitschrift*, for 1902, page 491, and a later form in the same Journal for

Fig. 8.

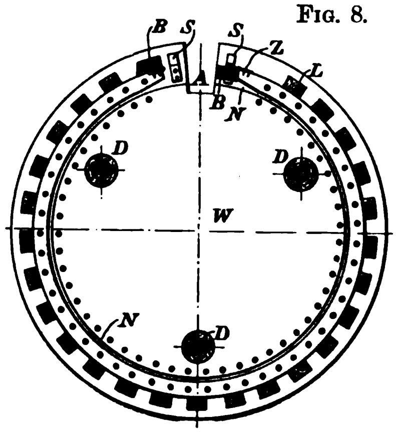

Fig. 9.

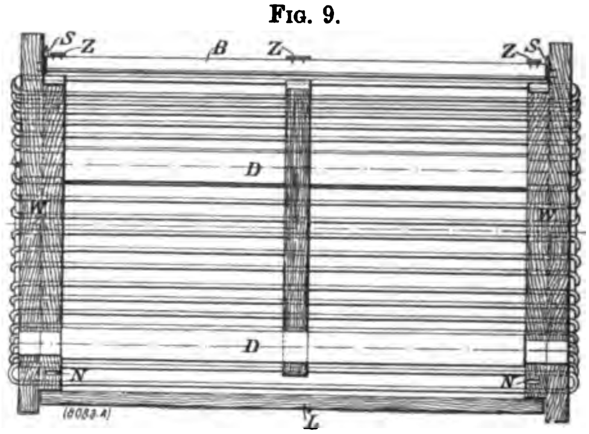

Fig. 10.

Figs. 8 to 10. Apparatus for Magnetic Tests of Whole Sheets of Iron.

1903, page 341, in an article entitled "Eisenprüfapparat für ganze Blechtafeln," by R. Richter. The apparatus is illustrated in Figs. 8, 9, and 10.

Properties of Materials

The magnetic properties of iron and steel depend upon the physical structure; as a primary indication of which, and as a specific basis for the description of the material, chemical analysis forms an essential part of tests. The physical structure and the magnetic properties are effected to a greater or less degree according to the chemical composition; by annealing, tempering, continued heating, and mechanical strains by tension or compression. The rate of cooling also influences the magnetic properties of the material; the permeability of cast iron, for instance, is diminished if the cooling has been too rapid, but it may be restored by annealing, the only noticeable change being that the size of the flakes of graphite is increased. The permeability of high carbon steels may also be increased by annealing and diminished by tempering, and that of wrought iron or steel is diminished by mechanical strain; the loss of permeability resulting from mechanical strain, may, however, be restored by annealing.

The effect on the magnetic properties, of the different elements entering into the composition of iron and steel, varies according to the percentage of other elements present. The presence of an element which, alone, would be objectionable may not be so when a number of others are also present; for instance, manganese in ordinary amounts is not objectionable in iron and steel, as the influence it exerts is of the same nature as that of carbon, but greatly less in degree. Some elements modify the influence of others, while some, although themselves objectionable, act as an antidote for more harmful impurities: as for instance, in cast iron, silicon tends to off-set the injurious influence of sulphur. The relative amounts and the sum of the various elements vary slightly, according to the slight variations in the process of manufacture. On account of the more or less unequal diffusion of the elements, a single analysis may not indicate the average quality, and may not, in extreme cases, fairly represent the quality of the sample used in the magnetic test. It is necessary, therefore, to make a great number of tests and analyses before arriving at an approximate result as to the effect of any one element. The conclusions here set forth, as to the effect of various elements, when acting with the other elements generally present, are the result of studying the analyses and magnetic values when the amounts of all but one of the principal elements remained constant. The results so obtained were compared

with tests in which the elements that had remained constant in the first test varied in proportion.

It will be seen that this method is only approximate, since variations of the amount of any element may modify the interactions between the other elements. The statements herein set forth have been compared with a great number of tests, and have been found correct within the limits between which materials can be economically produced in practice.

In general, the purer the iron or steel, the more important is the uniformity of the process and treatment, and the more difficult it is to predict the magnetic properties from the chemical analysis. It is significant to note that, beginning with the most impure cast iron, and passing through the several grades of cast iron, steel and wrought iron, the magnetic properties accord principally with the amounts of carbon present, and in a lesser degree with the proportions of silicon, phosphorus, sulphur, manganese, and other less usual ingredients, and that an excess of any one, or of the sum of all the ingredients, has a noticeable effect on the magnetic properties. Carbon, on account of the influence it exerts on the melting point, may be regarded as the controlling element as it determines the general processes; hence also the percentage of other elements present in the purer grades of iron. However, its influence may sometimes be secondary to that of other impurities; as, for instance, in sheet iron, where a considerable percentage of carbon has been found to permit of extremely low initial hysteresis loss, and to exert an influence tending to maintain the loss at a low value during subjection to prolonged heating.

The properties of iron and steel require separate examination as to magnetic permeability and magnetic hysteresis. The permeability is of the greatest importance in parts in which there is small change in the magnetisation; hence such parts may be of any desired dimension, and may then be either cast, rolled, or forged. On account of the electrical losses by local currents when the magnetism is reversed in solid masses of metals, parts subjected to varying magnetic flux have to be finely laminated. Thicknesses of between .014 in. and .036 in. are generally found most useful for plates, which must be of good iron to withstand the rolling process. Some impurities affect the hysteresis more than the permeability. Hysteresis tends towards a minimum, and the permeability towards a maximum, as the percentage of elements, other than iron, diminishes.

In the case of comparatively pure iron or steel, alloyed with nickel, it is found, however, that the permeability is increased beyond that which would be inferred from the other elements present. The purest iron has been found to have the highest permeability,[1] yet the iron in which the hysteresis loss has been found smallest is not remarkable for its purity, and there was no known cause why the hysteresis was reduced to such a noticeable extent. The treatment of the iron, both during and subsequent to its manufacture, exerts a great influence upon the final result.

The Magnetisation of Iron and Steel

Cast Iron.—Cast iron is used for magnetic purposes on account of the greater facility with which it may be made into castings of complex form. Considering the relative costs and magnetic properties of cast iron and steel, as shown in the curves, Figs 11 to 14, page 21, it is evident that cast iron is, other things being equal, more costly for a given magnetic result than cast steel. The great progress in the manufacture of steel castings has rendered the use of cast iron exceptional in the construction of well-designed electrical machines.

The cast iron used for magnetic purposes contains, to some extent, all those elements which crude iron brings with it from the ore and from the fluxes and fuels used in its reduction. Of these elements, carbon has the greatest effect on the magnetic permeability. The amount of carbon present is necessarily high, on account of the materials used, the process employed, and its influence in determining the melting point. In cast iron of good magnetic quality, the amount of carbon varies between 3 per cent. and 4.5 per cent.; between 0.2 per cent., and 0.8 per cent. being in a combined state,[2] and the remainder in an uncombined or graphitic state.

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[1] Exceptions are found in the case of a few alloys described in "Conductivity and Magnetic Properties of Iron Alloys," by W. F. Barrett, W. Brown and R. A. Hadfield, *Journal*, Institution of Electrical Engineers, vol. 31, pp. 674-721:—97¾ per cent. iron and 2¼ per cent. aluminium has nearly twice the permeability of pure iron for small densities; 97½ per cent. iron and 2½ per cent. silicon have also a greater permeability than pure iron. See also the paper read by the same authors before the Royal Dublin Society, *Transactions*, vol. 8, pp. 1-22, September, 1902.

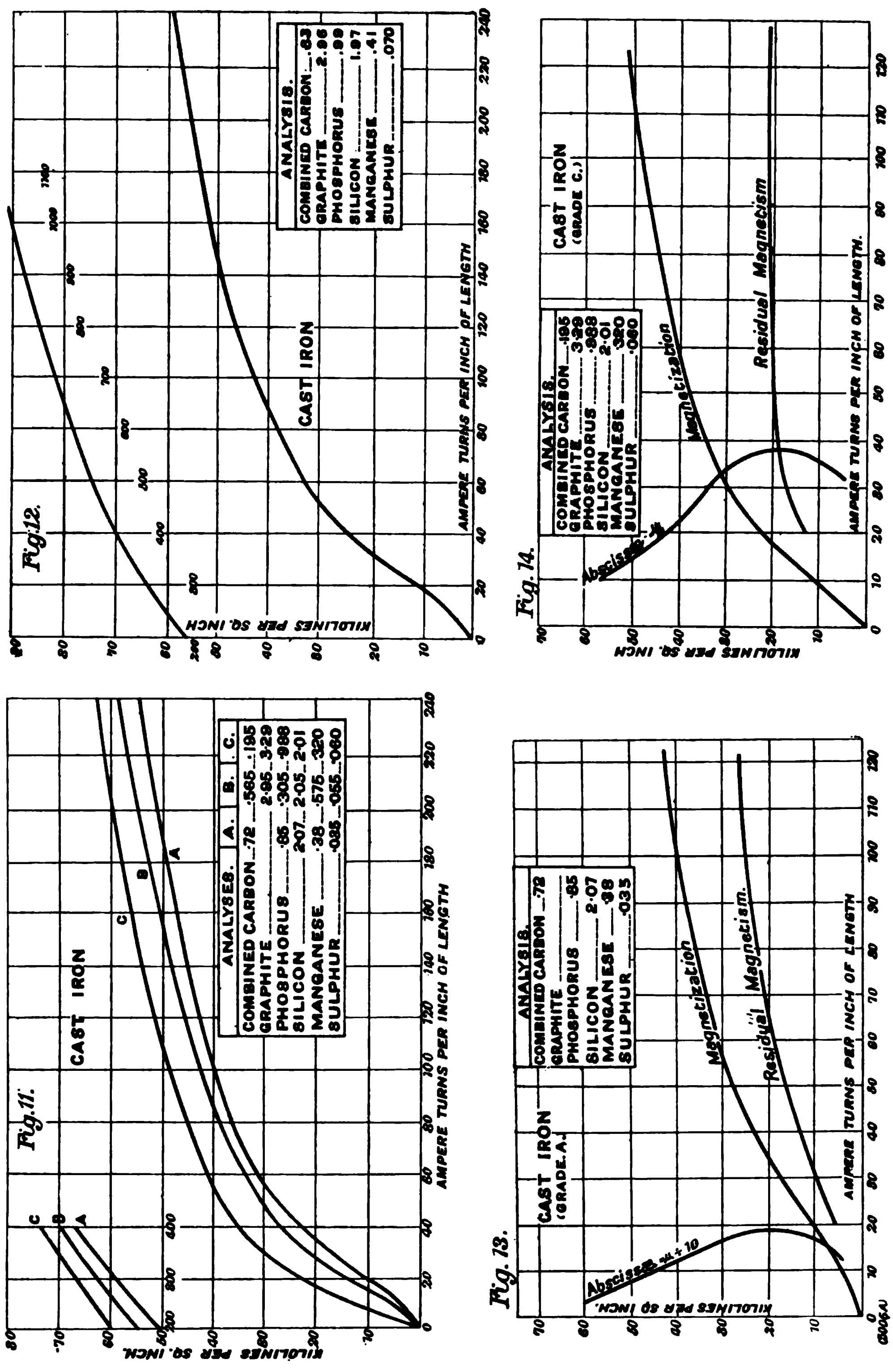
[2] Arnold, "Influence of Carbon on Iron," *Proceedings*, Institution of Civil Engineers, vol. cxxiii., page 156.

Combined carbon is the most objectionable ingredient, and should be restricted to as small an amount as possible. Cast irons having less than 0.3 per cent. of combined carbon are generally found to be of high magnetic permeability. Fig. 11 shows curves and analyses of three different grades of cast iron. The effect of different proportions of combined carbon may be ascertained by comparison of the results with the analyses shown on the diagrams. In Fig. 12 is given the result of the test of a sample carried up to a very high saturation. It is useful for obtaining values corresponding to high magnetisation, but as shown by the analyses and also by the curve, it is a sample of rather poor cast iron, the result being especially bad at low magnetisation values. The cast iron generally used for magnetic purposes would be between curves B and C of Fig. 11.

Graphite may vary between 2 per cent. and 3 per cent. without exerting any very marked effect upon the permeability of cast iron. It is generally found that when the percentage of graphite approximates to the lower limit, there is an increase in the amount of combined carbon and a corresponding decrease of permeability. A certain percentage of carbon is necessary, and it is desirable that as much of it as possible should be in the graphitic state. Sulphur is generally present, but only to a limited extent. An excess of sulphur is an indication of excessive combined carbon, and inferior magnetic quality. Silicon in excess annuls the influence of sulphur, and does not seem to be objectionable until its amount is greater than 2 per cent., its effect being to make a casting homogeneous, and to lessen the amount of combined carbon. The amount of silicon generally varies between 2.5 per cent. in small castings, and 1.8 in large castings. Phosphorus in excess denotes an inferior magnetic quality of iron. Although in itself it may be harmless, an excess of phosphorus is accompanied by an excess of combined carbon, and it should be restricted to 0.7 per cent. or 0.8 per cent. Manganese, in the proportions generally found, has but little effect; its influence becomes more marked in irons that are low in carbon.

Figs. 13 and 14 give further data relating to irons shown in Fig. 11, grades A and C respectively.

Malleable Cast Iron.—When cast iron is decarbonised, as in the process for making it malleable, in which a portion of the graphite is eliminated, there is marked increase in the permeability. This is due, however, to the change in the physical structure of the iron which accompanies the decarbonisation, as unmalleable cast iron, of chemical analysis



Figs. 11 to 14. Magnetic Curves for Cast Iron

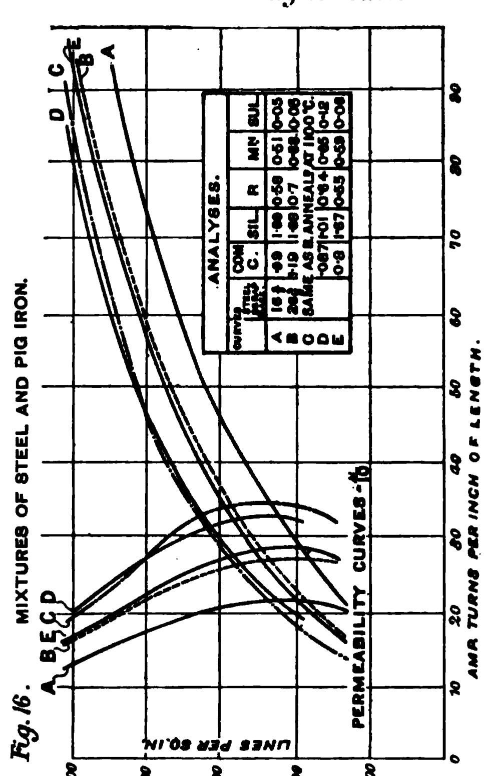
identical with that of malleable iron, has but a fraction of the permeability. In Fig. 15 are shown the magnetic properties of malleable cast iron; Fig. 16 illustrates the magnetic properties of mixtures of steel and pig iron.

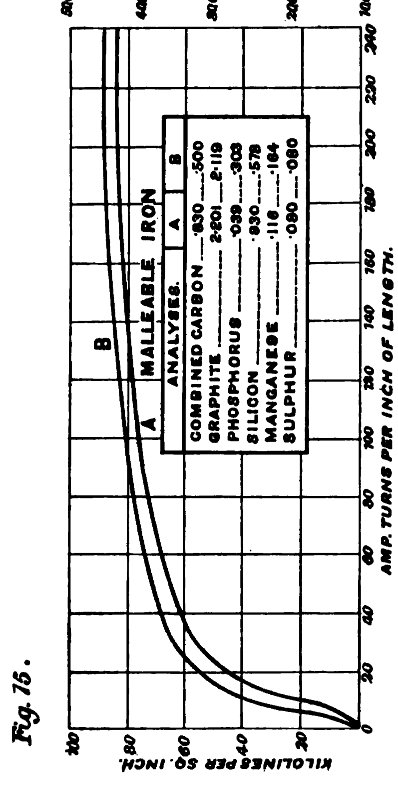
Cast Steel.—The term "cast steel," as used in this place, is intended to refer to recarbonised iron, and not to the processes of manufacture where there has been no recarbonisation, as in irons made by the steel process. Cast steel used for magnetic purposes has been generally made by the open-hearth or Siemens-Martin process, the principal reason being that this process has been more frequently used for the manufacture of small castings. The Bessemer process could, perhaps, be used to greater advantage in the manufacture of small castings than the open-hearth process, since, on account of the considerable time elapsing between the pouring of the first and last castings, there is frequently by the open-hearth process a change of temperature in the molten steel, and likewise a noticeable difference in the magnetic quality. In the Bessemer process the metal can be maintained at the most suitable temperature, and the composition is more easily regulated.

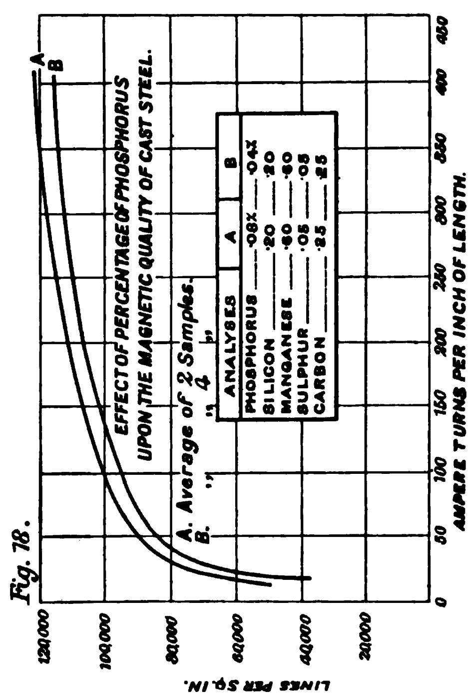
Cast steel is distinguished by the very small amount of carbon present which is in the combined state, there being generally no graphite, as in the case of cast iron, the exception being when castings are subjected to great strains, in which case the combined carbon changes to graphite. It may be approximately stated that good cast steel, from a magnetic standpoint, should not have greater percentages of impurities than the following:—

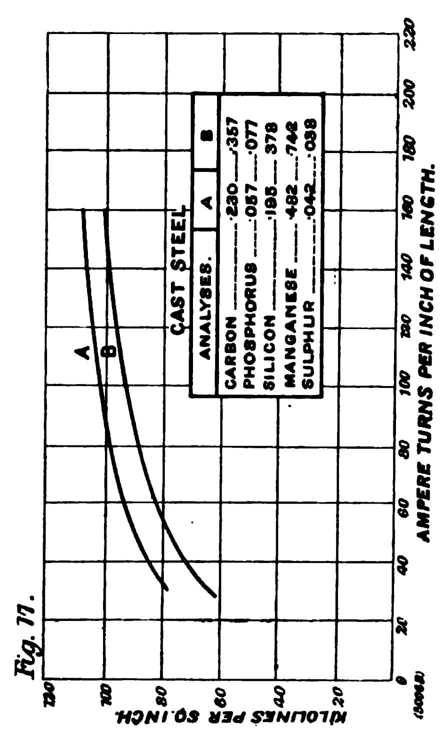
	Per Cent.
Combined carbon	0.25
Phosphorus	0.08
Silicon	0.20
Manganese	0.50
Sulphur	0.05

In practice, carbon is the most objectionable impurity, and may be with advantage restricted to smaller amounts than 0.25 per cent. The results of a great number of tests and analyses show that the decrease in the permeability is proportioned to the amount of carbon in the steel, other conditions remaining equal; that is, that the other elements are present in the same proportion, and that the temperature of the molten steel is









FIGS. 15 TO 18. MAGNETIC CURVES FOR MALLEABLE IRON, STEEL AND PIG IRON, AND CAST STEEL

increased according to the degree of purity. Cast steel at too low a temperature considering the state of purity, shows a lower permeability than would be inferred from the analysis. Manganese in amounts less than 0.5 per cent. has but little effect upon the magnetic properties of ordinary steel. In large proportions, however, it deprives steel of nearly all its magnetic properties, a 12 per cent. mixture scarcely having a greater permeability than air. Silicon, at the magnetic densities economical in practice, is less objectionable than carbon, and at low magnetisation increases the permeability up to 4 or 5 per cent;[1] but at higher densities it diminishes the permeability to a noticeable extent. The objection to silicon is that when unequally diffused it facilitates the formation of blow-holes and, like manganese, has a hardening effect, rendering the steel difficult to tool in machining. Phosphorus and sulphur, in the amounts specified, are not objectionable; but in excess they generally render the steel of inferior magnetic quality.

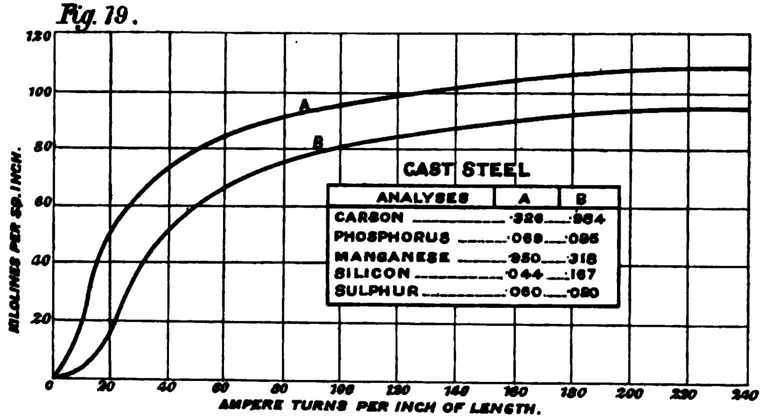
In Tables I. and II. are given the analyses and magnetic properties of what may be termed good and poor steel respectively. In Fig. 17, curves A and B represent the average values corresponding to these two sets of tests (see page 23).

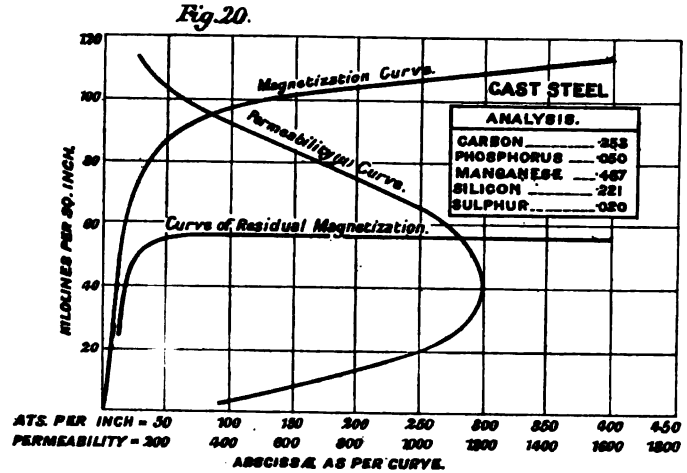
The extent to which the percentage of phosphorus affects the result may be seen from the curves of Fig. 18. The curves of Fig. 19 show the deleterious effect of combined carbon upon the magnetic properties. The magnetic properties of steel are further illustrated in Figs. 20, 21, and 22.

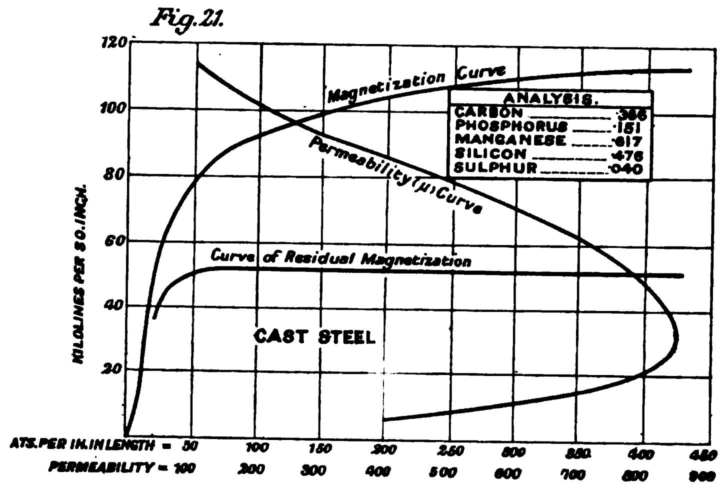
TABLE I.—DATA OF TEN FIRST QUALITY SAMPLES OF CAST STEEL

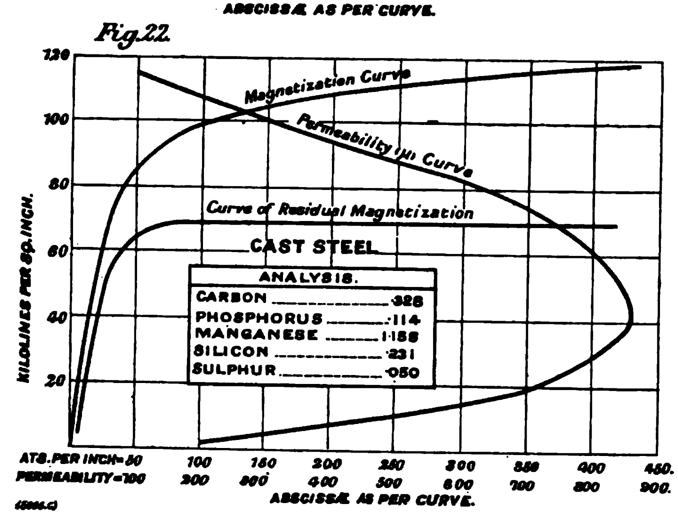
Ampere-Turns per Inch of Length.	Kilolines per Square Inch.										
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	Average.
30	78.6	77.5	78.0	83.2	84.0	79.4	84.5	78.0	81.4	84.0	80.9
50	91.0	87.7	89.6	93.0	94.2	89.6	93.5	88.5	91.5	93.5	91.2
100	102	98.6	100	102	107	100	104	99.4	102	103	101.8
150	107	104	107	106	113	106	110	105	108	107	107.3
	Analysis.										
Carbon	.240	.267	.294	.180	.290	.250	.200	.230	.170	.180	.230
Phosphorus ...	.071	.052	.074	.047	.037	.093	.047	.100	.089	.047	.057
Silicon	.200	.236	.202	.120	.036	.230	.173	.160	.150	.120	.195
Manganese ...	.480	.707	.655	.323	.550	.410	.530	.450	.390	.323	.482
Sulphur... ...	.040	.060	.050	.050	.050	.030	.030	.040	.020	.050	.042

[1] See *Electrical World*, December 10th, 1898, page 619.









FIGS. 19 TO 22. MAGNETIC CURVES FOR CAST STEEL

TABLE II.—DATA OF TEN SECOND QUALITY SAMPLES OF CAST STEEL

Ampere-Turns per Inch of Length.	Kilolines per Square Inch.										
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	Average.
30	68.3	68.3	69.0	58.0	60.0	64.5	67.0	64.5	60.0	73.0	65.3
50	82.0	82.0	84.5	72.2	74.8	78.0	80.5	80.0	76.0	87.0	79.7
100	96.0	94.1	97.5	87.0	89.6	92.2	92.9	94.8	91.0	101	93.6
150	102	100	102	92.8	96.0	98.7	98.7	101	96.5	106	99.4
					Analysis.						
Carbon	.250	.280	.195	.333	.337	.366	.409	.318	.702	.380	.357
Phosphorus ...	.087	.076	.028	.059	.045	.151	.063	.107	.084	.066	.077
Silicon	.210	.210	.683	.292	.302	.476	.444	.203	.409	.550	.378
Manganese ...	.790	.720	.815	.681	.642	.617	.640	1.636	.088	.790	.742
Sulphur... ...	.020	.030	.040	.060	.070	.010	.010	.030	.050	.030	.038

Mitis Iron.—In Table III. are given analyses and magnetic properties of aluminium steel, frequently referred to as "mitis iron." The action

TABLE III.—DATA OF TWELVE SAMPLES OF MITIS IRON

Ampere-Turns per Inch of Length.	Kilolines per Square Inch.												
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	Average.
30	81.3	93.5	93.5	82.0	89.6	91.5	90.3	69.6	64.5	83.1	82.0	76.0	83.1
50	87.6	100	101	93.5	96.8	101	98.6	81.6	76.7	92.	92.2	86.5	92.3
100	95.5	109	108	104	105	108	106	92.0	89.5	102	103.	96.5	101.5
150	100	114	113	109	110	112	110	98.0	95.5	108	108.	101	106.5
						Analysis.							
Carbon	.065	.105	.106	.125	.136	.212	.214	.216	.235	.241	.242	.260	.180
Phosphorus ...	.083	.093	.112	.166	.053	.056	.052	.128	.065	.093	.094	.120	.093
Silicon	.073	.045	.050	.046	.111	.126	.111	.083	.122	.072	.099	.020	.080
Manganese ...	.112	.108	.099	.120	.191	.405	.401	.167	.107	.248	.253	.140	.196
Sulphur... ...	.150	.050	.050	.050	.030	.040	.040	.010	.030	.030	.030	.030	.045
Aluminium ...	.079	*	.059	.183	.008	.273	*	.152	.055	.120	.119	.080	.113

* Not determined.

of aluminium in steel is, like that of silicon, sulphur, or phosphorus, of a softening nature. It seems to act more powerfully than silicon, the castings having a somewhat greater degree of purity and a higher magnetic quality than steel castings made by processes of equal refinement. It will be seen from the analyses that the aluminium is present in amounts ranging from 0.05 per cent. to 0.2 per cent., and that this permits of making

good castings with about one-half as much silicon and manganese as in ordinary cast steel. The amount of carbon, also, is generally somewhat less. An inspection of these tests and analyses of mitis iron shows that they do not furnish a clear indication as to the effect of the various impurities. It will be noticed, however, that in those of poor magnetic qualities there is generally an excess of impurities, this excess denoting a lack of homogeneity and a greater degree of hardness than in those of good quality.

Mitis iron is, magnetically, a little better than ordinary steel up to a density of 100 kilolines, but at high densities it is somewhat inferior. The magnetic result obtained from mitis iron up to a density of 100 kilolines is practically identical with that obtained from wrought-iron forgings.

A curve representing the average of the twelve samples of Table III., is given in Fig. 23, page 28.

Nickel Steel.—Some of the alloys of steel with nickel possess remarkable magnetic properties.[1] A 5 per cent. mixture of nickel with steel, shows a greater permeability than can be accounted for by the analysis of the properties of the components. The magnetic properties of nickel alloys are shown in Fig. 24.[2]

Forgings.—Forgings of wrought iron are, in practice, found to be of uniform quality and of high magnetic permeability. In curves A and B of Fig. 25 are shown the magnetic properties of wrought iron, nearly pure, and as generally obtained, respectively. The former is made by the steel process at the Elswick Works of Messrs. Sir W. G. Armstrong and Co., Limited, but owing to its excessively high melting point, it is only manufactured for exceptional purposes. Curve D illustrates an inferior grade of wrought iron, its low permeability being attributable to the excess of phosphorus and sulphur. Curve B shows the properties of a forging of Swedish iron, in the analysis of which it is somewhat remarkable to find a small percentage of graphite.

For the wrought-iron forgings and for the sheet iron and sheet steel generally used, curve B should preferably be taken as a basis for calcula-

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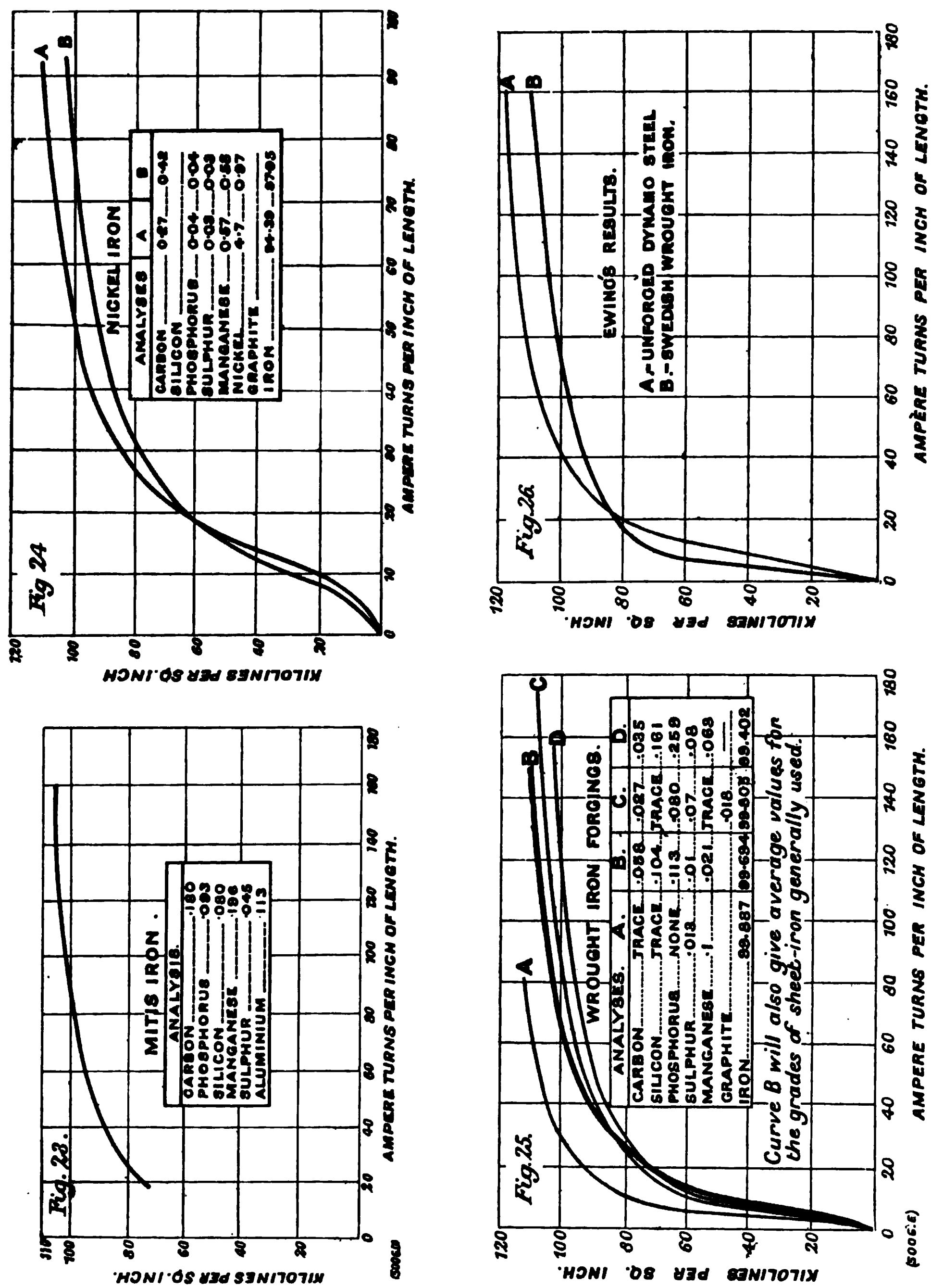
[1] For information as to the remarkable conditions controlling the magnetic properties of the alloys of nickel and iron, see Dr. J. Hopkinson, *Proceedings*, Royal Society, vol. xlvii., page 23, and vol. xlviii., page 1. See also R. Paillot, *Comptes Rendus*, page 132, May 13th, 1901

[2] Various investigations have shown that the permeability of steel is greatly lessened by the presence of chromium and tungsten.



Figs 23 to 26. Magnetic Curves for Mitis Iron, Nickel Steel, Steel and Wrought Iron

tions, although the composition of the sheets will not be that given by the analyses. The composition of some samples of sheet iron and sheet steel, the results of tests of which are set forth on pages 33 to 35, is given in Table IV. Such material, however, is subject to large variations in magnetic properties, due much more to treatment than to composition.

TABLE IV.—ANALYSIS OF SAMPLES

Brand.	Silicon.	Phosphorus.	Manganese.	Sulphur.	Carbon.
I.	.019	Not determined	.490	Not determined	.120
II.	.007	Not determined	.420	Not determined	.062
III.	.009	.083	.510	.026	.056
IV.	.003	Not determined	.570	Not determined	.044
V.	trace	.029	.020	trace	.050
VI.	.005	.059	.500	.048	.040
VII.					
VIII.	.003	.018	.490	.014	.052
IX.					
X.					

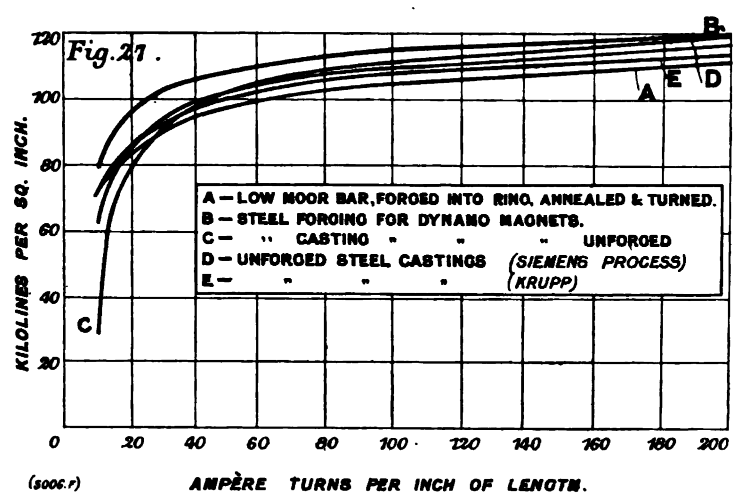


FIG. 27. MAGNETIC CURVES FOR FORGINGS AND STEEL CASTINGS

In comparing wrought-iron forgings with unforged steel castings, Professor Ewing notes[1] that the former excel in permeability at low densities, and the latter at high densities. This he illustrates by the curves reproduced in Fig. 26, in which are given results for Swedish wrought iron and for a favourable example of unforged dynamo steel

[1] *Proceedings*, Institution of Civil Engineers, May 19th, 1896.

by an English maker. He states that annealed Lowmoor iron would almost coincide with the curves for Swedish iron.

Professor Ewing further states that there is little to choose between the best specimens of unforged steel castings and the best specimens of forged ingot metal. The five curves of Fig. 27, page 29, relate to results of his own tests, with samples of commercial iron and steel. Of these curves, A refers to a sample of Lowmoor bar, forged into a ring, annealed and turned; B to a steel forging furnished by Mr. R. Jenkins as a sample of forged ingot metal for dynamo magnets; C to an unforged steel casting for dynamo magnets made by Messrs. Edgar Allen and Co. by a special pneumatic process; D to an unforged steel casting for dynamo magnets made by Messrs. Samuel Osborne and Co. by the Siemens process; E to an unforged steel casting for dynamo magnets made by Messrs. Friedrich Krupp, of Essen.[1]

The Testing of Castings and Forgings in Bulk by Ballistic Galvanometer

Instead of cutting a small ring from the sample, it has been suggested by Dr. Drysdale[2] to cut an annular recess in the casting or forging whose

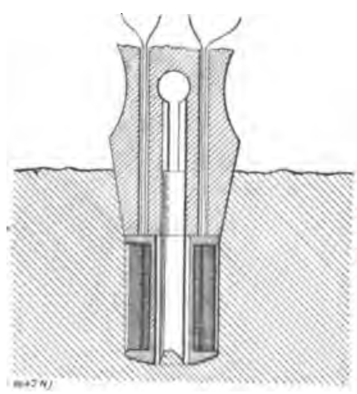


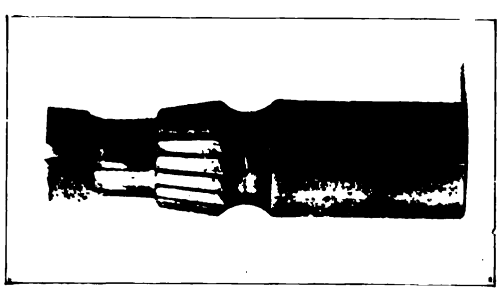
Fig. 28. Section through Plug and Specimen, Dr. Drysdale's Test

magnetic quality is in question, and after locating an exciting and exploring coil therein, to close the recess with a plug, and to make the permeability

[1] *Proceedings*, Institution of Civil Engineers, May 19th, 1896.

[2] "A Permeameter for Testing the Magnetic Qualities of Materials in Bulk," *Journal*, Institution of Electrical Engineers, vol. xxxi., page 283.

PLATE I



Dr. Drysdale's Direct-Reading Permeability Testing Set

tests by the methods employed on ring samples. Obviously, it is a distinct advantage to make the tests on the actual casting or forging, instead of on a small detached sample. The idea is illustrated by the section through plug and specimen shown in Fig. 28, taken from the paper above referred to.

Energy Losses in Sheet Iron

The energy loss in sheet iron in an alternating or rotating magnetic field consists of two distinct quantities, the first being that by hysteresis or inter-molecular magnetic friction, and the second that by eddy currents. The loss by hysteresis is proportional to the frequency of the reversal of the magnetism, but is entirely independent of the thickness of the iron, and increases with the magnetisation. There is no exact law of the increase of the hysteresis with the magnetisation, but within the limits of magnetisation obtaining in practice, and those in which such material can be produced to give uniform results, the energy loss by hysteresis may be taken to increase approximately with the 1.6th power of the magnetisation, as was first pointed out by Mr. C. P. Steinmetz.[1]

Professor Ewing and Miss Klassen,[2] however, from a large number of tests, found the 1.48th power to be better representative at the densities generally met in transformers. Other extensive tests point to the 1.5th power as the average.[3]

The hysteresis loss is independent of the temperature at ordinary working temperatures, but from 200 deg. Cent. upward the loss decreases as the temperature increases, until at 700 deg. Cent. it has fallen to as low as from 10 per cent. to 20 per cent. of its initial value. Obviously this decrease at very high temperature is of no commercial importance at the present time.[4]

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[1] *Elec. Eng.*, New York, vol. x., page 677.

[2] *Electrician*, April 13th, 1894.

[3] *Elec. World*, June 15th, 1895.

[4] *Tech. Quarterly*, July, 1895; also *Elek. Zeit.*, April 5th, 1894; also *Phil. Mag.*, September, 1897; also in a very complete and valuable paper by D. K. Morris, Ph.D., "On the Magnetic Properties and Electrical Resistance of Iron as dependent upon Temperature," read before the Physical Society, on May 14th, 1897, are described a series of tests of hysteresis, permeability, and resistance, over a wide range of temperatures. Also R. L. Wills, "Effect of Temperature on Hysteresis Loss in Iron," *Phil. Mag.*, page 5, January 5th, 1903.

The magnitude of the hysteresis loss[1] is somewhat dependent upon the chemical composition of the iron, but to a far greater degree upon the physical processes to which the iron is subjected.

Annealing of Sheet Iron.—The temperature at which sheet iron is annealed has a preponderating influence upon the nature of the results obtained. Extended experiments concerning the relation of hysteresis loss to temperature of annealing, show that the higher the temperature the lower the hysteresis loss up to about 950 deg. Cent.[2] Beyond this temperature deleterious actions take place; the surfaces of the sheets become scaled, and the sheets stick together badly. A slight sticking together is desirable, as it insures the iron having been brought to the desired high temperature, and the sheets are easily separated; but soon after passing this temperature (950 deg. Cent.), the danger of injuring the iron becomes great.

Curves A and B of Fig. 29, page 33, show the improvement effected in two different grades of iron by annealing from high temperatures.[3]

Deterioration of Sheet Iron.—It has been found that the hysteresis loss in iron increases by continued heating.[4] No satisfactory explanation of the cause of this deterioration has yet been given. Its amount depends upon the composition of the iron, and upon the temperature from which it has been annealed. The best grades of charcoal iron, giving an exceedingly low initial loss, are particularly subject to deterioration through so-called "ageing." Iron annealed from a high temperature, although more

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[1] See the tests made by S. W. Richardson and L. Lownds (*Phil. Mag.*, June, 1901), on the subject of the influence of temperature on the hysteresis losses in an alloy of iron and aluminium. See also *Phil. Mag.*, page 49, January, 1900, and March, 1901; also *Elektrotechn. Zeitschr.*, April 25th, 1901.

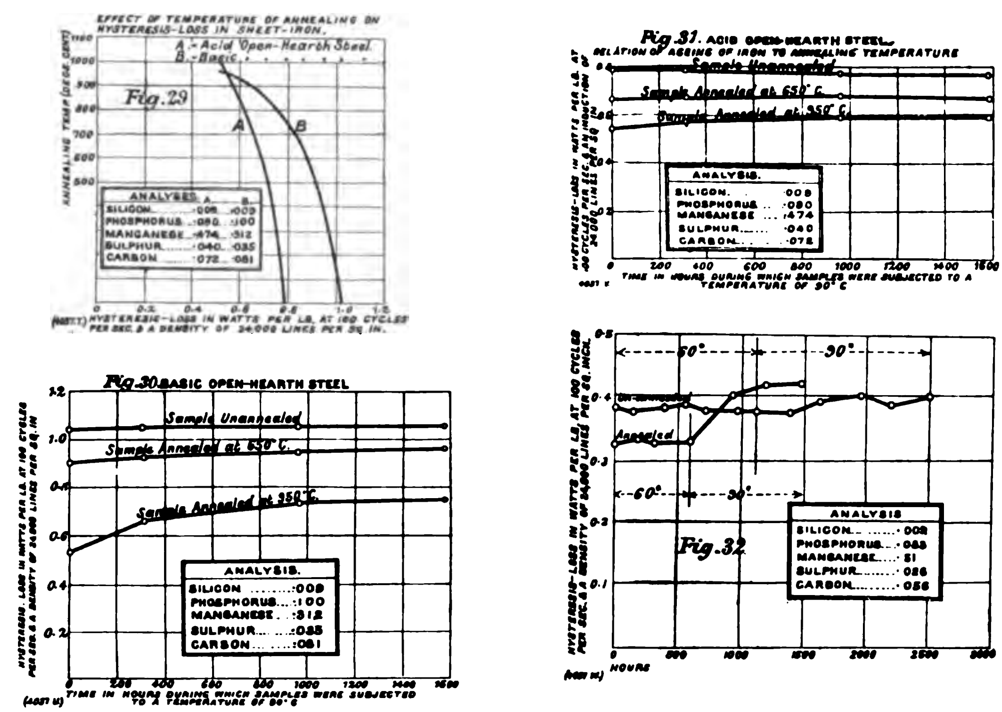
[2] This temperature depends somewhat upon the composition of the iron, being higher the more pure the iron. See E. Gumlich and E. Schmidt, *Elektrotechn. Zeitschr.*, August 29th, 1901.

[3] In this and much of the following work on hysteresis and on the properties of insulating materials, the authors are indebted to Mr. Jesse Coates, of Lynn, Mass., and to Messrs. R. C. Clinker and C. O. Wharton, of London, for valuable assistance in the carrying out of tests.

[4] "On Slow Changes in the Magnetic Permeability of Iron," by William M. Mordey, *Proceedings of the Royal Society*, January 17th, 1895; also *Electrician*, December 7th, 1894, to January 11th, 1895. A very valuable contribution to this subject has been made by Mr. S. R. Roget, in a paper entitled "Effects of Prolonged Heating on the Magnetic Properties of Iron," read before the Royal Society, May 12th, 1898. It contains some very complete experimental data. See also D. Mazzato, "Magnetic Ageing of Iron at Moderately High and at Ordinary Temperatures," N. Gimento, June and July, 1904.

subject to loss by "ageing," generally remains superior to the same grade of iron annealed from a lower temperature. This was the case in the tests corresponding to Figs. 30 and 31, but there are many exceptions.

Table V. shows the results of "ageing" tests at 60 deg. Cent. on several different brands of iron. It will be noticed that in the case of those brands subject to increase of hysteresis by "ageing," the percentage rise of the annealed sample is invariably greater than that of the



FIGS. 29 TO 32. EFFECT OF ANNEALING TEMPERATURE AND "AGEING" CURVES

unannealed sample, and that often the annealed sample ultimately becomes worse than the unannealed samples.

Brands III., V., and VI., are the same irons whose "ageing" records are plotted in Figs. 32, 33, and 35 respectively (see above, and on page 35).

From these investigations it appears that iron can be obtained which will not deteriorate at 60 deg. Cent., but that some irons deteriorate rapidly even at this temperature; and that at a temperature of 90 deg. Cent. even the more stable brands of iron deteriorate gradually. Consequently, so far as relates to avoidance of deterioration through "ageing," apparatus, even

TABLE V.—RESULTS OF TESTS ON AGEING OF IRON

(From Tests by R. C. Clinker, London, 1896-7.)

Temperature of ageing = 60 deg. Cent., except where otherwise stated.

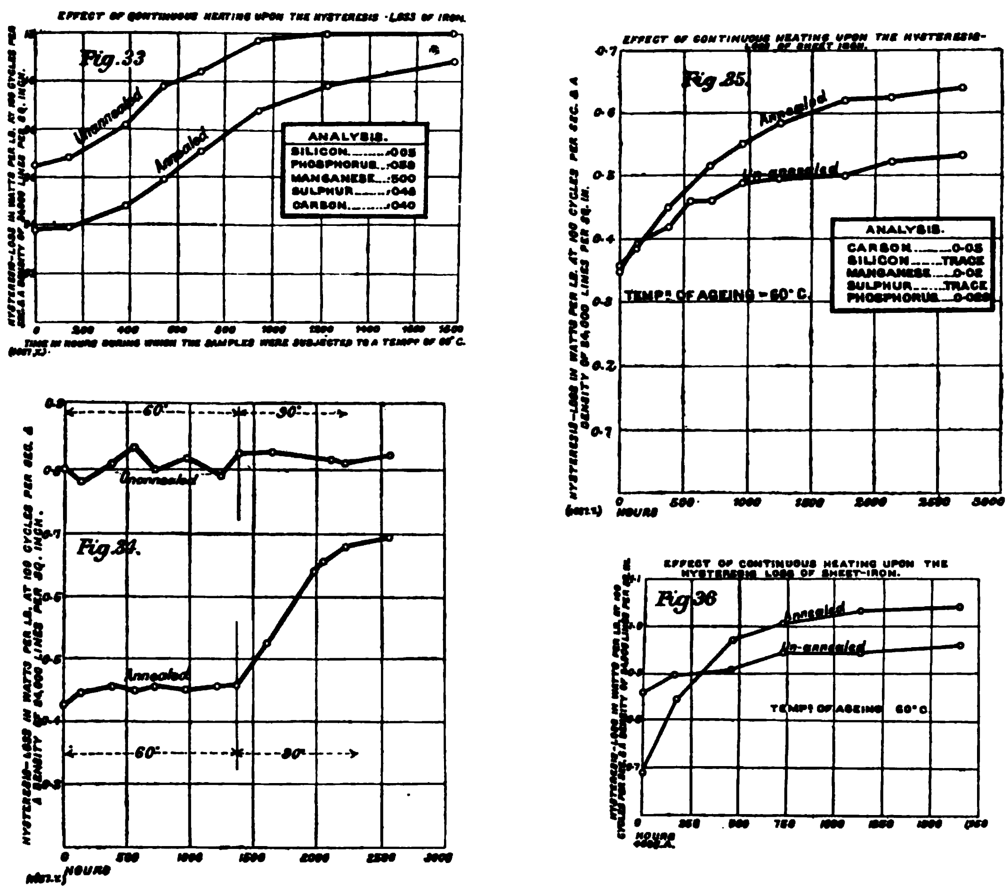
The chemical analyses of these samples are given in Table IV., on page 29.

Brand of Iron.	Hysteresis Loss in Watts per pound at 100 Cycles per Second, and 24,000 Lines per Square Inch.						Increase in 1000 hours.
	Initial Loss.	After Ageing for					
		200 Hours.	400 Hours.	600 Hours.	800 Hours.	1000 Hours.	
							per cent.
I.							
Unannealed	1.00	1.00	1.00	1.00	1.00	1.00	0
Annealed	0.41	0.43	0.43	0.43	0.43	0.43	5
II.							
Unannealed	0.46	0.46	0.46	0.46	0.46	0.46	0
Annealed	0.39	0.39	0.40	0.41	0.42	0.43	10
III.							
Unannealed	0.38	0.38	0.38	0.38	0.38	0.38	0
Annealed	0.33	0.33	0.33	0.33	0.37	0.39	18[1]
IV.							
Unannealed	0.86	0.90	0.94	0.97	1.01	1.04	21
Annealed	0.42	0.50	0.58	0.66	0.74	0.83	98
V.							
Unannealed	0.35	0.40	0.43	0.45	0.47	0.49	40
Annealed	0.36	0.40	0.45	0.50	0.53	0.55	53
VI.							
Unannealed	0.65	0.71	0.83	1.00	1.09	1.19	83
Annealed	0.39	0.41	0.49	0.62	0.78	0.90	130
VII.							
Unannealed	0.80	0.82	0.82	0.82	0.82	0.82	3
Annealed	0.43	8.44	0.45	0.45	0.45	0.45	6
VIII.							
Unnannealed	0.36	0.36	0.36	0.36	0.37	0.37	3
Annealed	0.31	0.32	0.34	0.35	0.35	0.35	13
IX	0.58	0.58	0.58	0.58	0.60	0.64	10[2]
X.	0.42	0.42	0.42	0.43	0.47	0.56	33[3]

[1] Temperature raised to 90 deg. after 600 hours.
[2] Temperature raised to 90 deg. after 650 hours.
[3] Temperature raised to 90 deg. after 670 hours.

when constructed with selected irons, should not be allowed to reach a temperature much above 60 deg. Cent.

An examination of the results indicates that a rather impure iron gives the most stable result. It is believed that by annealing from a sufficiently high temperature, such impure iron may be made to have as



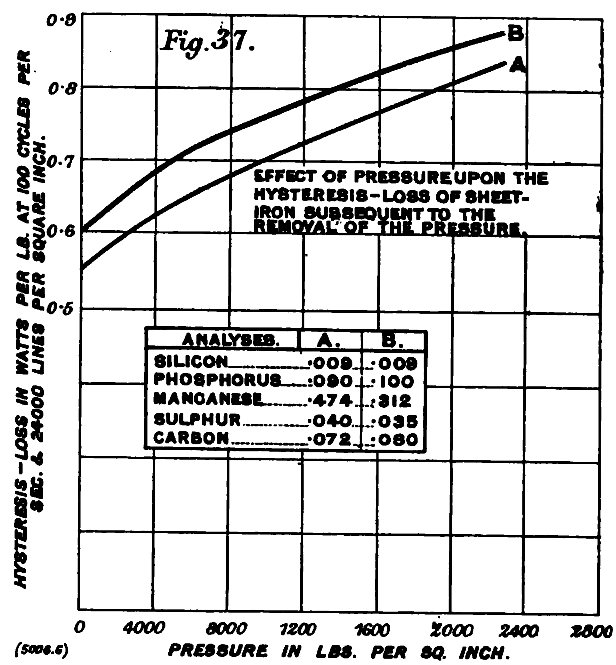
FIGS. 32 TO 36. "AGEING" CURVES FOR SHEET IRON

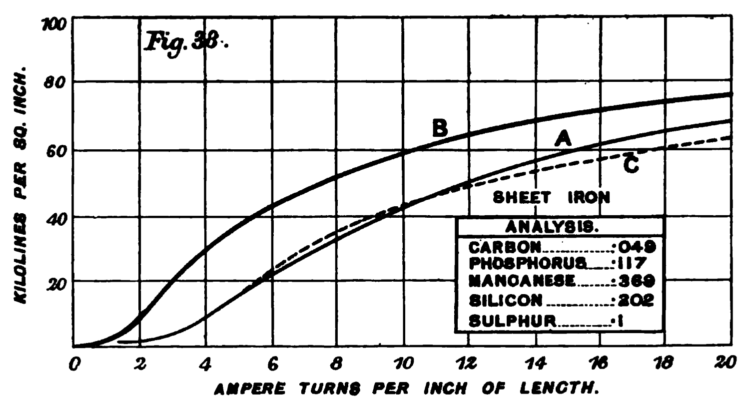
low an initial hysteresis loss as can be obtained with the purest iron. The lower melting point of impure iron, however, imposes a limit; for such iron cannot, in order to anneal it, be brought to so high a temperature as pure iron, because the surface softens and the plates stick together at comparatively low temperatures.

The curves of Figs. 34, 35, and 36 represent the results of interesting "ageing" tests. In Fig. 34 the effect of a higher temperature upon the annealed sample is clearly shown.

A good low "ageing" sheet steel may generally be produced with the following composition :—

	Per Cent.
Silicon	0.01
Phosphorus	0.08
Manganese	0.5
Sulphur	0.03
Carbon	0.06



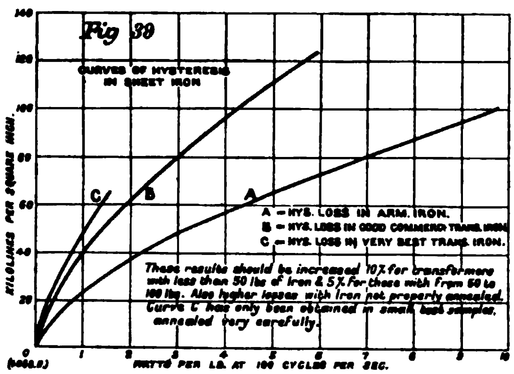


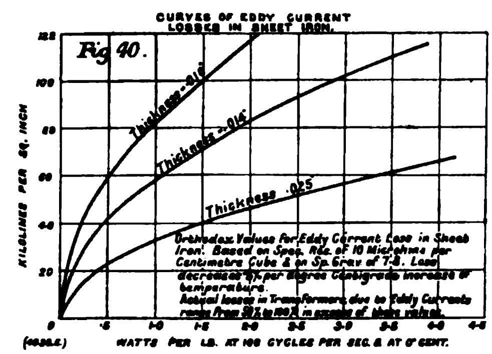
FIGS. 37 AND 38. EFFECT OF PRESSURE UPON HYSTERESIS LOSS IN SHEET IRON

It is often the very cheapest qualities of sheet steel which are the most suitable as regards magnetic quality and freedom from "ageing."

Effect of Pressure.—Pressure and all mechanical strains are injurious even when of no great magnitude, as they decrease the permeability and increase the hysteretic loss. Even after release from pressure, the iron only partly regains its former good qualities. In the curves of Fig. 37, page 36, is shown the effect of applying pressure to two different grades of iron, the measurements having been made after the removal of the pressure.

Another interesting case is that shown in the curves A, B, and C, of Fig. 38. These show the results of tests upon a certain sample of sheet iron, as it was received from the makers, after it had been annealed, and after being subjected to a pressure of 40,000 lb. per square inch, respectively.





FIGS. 39 AND 40. CURVES FOR HYSTERESIS AND EDDY CURRENT LOSSES IN SHEET IRON

It will be seen that the annealing in this case materially increased the permeability, but that subjecting the sample to pressure diminished the permeability below its original value.

The value of the hysteresis losses while the iron is still under pressure is probably much greater. Mr. Mordey refers to a case in which a pressure of 1500 lb. per square inch was accompanied by an increase of 21 per cent. in the core loss. Upon removing the pressure, the core loss fell to its original value.[1] Re-annealing restores iron which has been injured by pressure, to its original condition.

This matter of injury by pressure, particularly so far as relates to the increase while the iron remains under pressure, is one of considerable

[1] "On Slow Changes in the Magnetic Permeability of Iron," by William M. Mordey, *Proceedings*, Royal Society, January 17th, 1895.

importance, and in assembling armature and transformer sheets, no more temporary or permanent pressure should be used than is essential to good mechanical construction.

Hysteresis Loss.—The curves of Fig. 39 give values for the hysteresis losses that can be obtained in actual practice. Curve B is for sheet steel such as should be used for transformer construction, and all iron used in transformer work should be required to comply with these values. For transformer work, iron of .014 in. thickness is generally used.

For armature iron there is no occasion for such exacting requirements, and curve A is representative of the armature iron generally used. Iron for armatures is usually .025 in. to .036 in. in thickness. Curve C gives the best result yet secured by Professor Ewing. It was from a strip of transformer plate .013 in. thick, rolled from Swedish iron.[1] Its analysis was:

	Per Cent.		Per Cent.
Carbon	.02	Phosphorus	.020
Silicon	.032	Sulphur	.003
Manganese ...	trace only.	Iron (by difference) ...	99.925

This iron ages very rapidly. The iron of Fig. 32, page 33, is only 6 per cent. worse initially when annealed, and at 60 deg. Cent. it does not deteriorate. Its analysis has already been given.

Eddy Current Losses

In sheet iron the eddy current losses should theoretically conform to the formula:[2]

$$W = 1.50 \times t^2 \times N^2 \times B^2 \times 10^{-10}.$$

in which

W = watts per pound at 0 deg. Cent.
t = thickness in inches.
N = periodicity in cycles per second.
B = density in lines per square inch.

The loss decreases .5 per cent. per degree Centigrade increase of temperature. The formula holds for iron, whose specific resistance is

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[1] *Proceedings*, Institution of Civil Engineers, May 19th, 1896.

[2] For thicknesses greater than .025 in., magnetic screening greatly modifies the result. Regarding this, see Professor J. J. Thomson, London, *Electrician*, April 8th, 1892. Professor Ewing, London, *Electrician*, April 15th, 1892.

10 microhms per centimetre cube, at 0 deg. Cent., and which has a weight of .282 lb. per cubic inch. These are representative values for the grades used, except that in sheet steel the specific resistance is apt to be considerably higher.

Curves giving values for various thicknesses of iron are shown in Fig. 40, page 37.

Owing possibly to the uneven distribution of the flux, particularly at the joints, the observed eddy current losses are, in transformer iron, from 50 to 100 per cent. in excess of these values, even when the sheets are insulated with Japan varnish or otherwise.

Estimation of Armature Core Losses.—As regards the use of curve A, of Fig. 39, in estimating armature core losses, the values obtained from curve A may for practical purposes be considered to represent the hysteresis component of the total loss. To allow for other components of the total core loss, the values obtained from curve A should be multiplied by from 1.3 to 2.5, according to the likelihood of additional losses. Briefly, this large allowance for eddy current losses in armature iron is rendered necessary owing to the effect of machine work, such as turning down, filing, &c., these processes being destructive to the isolation of the plates from each other.

The curves in Fig. 40, page 37, are chiefly useful for transformer work, and are of little use in armature calculation, as they refer only to the eddy current losses due to eddy currents set up in the individual isolated sheets, and in armatures this often constitutes but a small part of the total loss.

The irons used for magnetic purposes have approximately the resistance and density constants given in Table VI.; in which are also given, for comparison, the corresponding values for very pure iron and for commercial copper:

TABLE VI

—	Specific Resistance at 0 deg. Cent. Microhms per Centimetre Cube.	Increase in Resistance per deg. Cent.	Specific Gravity.	Pounds per Cubic Inch.
		per cent.		
Cast iron	100	.1	7.20	.260
Cast steel	20	.4	7.80	.282
Wrought iron and very mild steel	10	.5	7.80	.282
Nearly pure iron	9	.6	—	—
Commercial copper	1.6	.388	8.90	.322

Mr. W. H. Preece, (Munroe and Jameson Pocket-book), gives the Table of Values, reproduced below, which shows in a striking manner the dependence of the specific resistance of iron upon the chemical composition.

TABLE VII.—PREECE'S TESTS OF ANNEALED IRON WIRE

Number of Sample.	1.	2.	3.	4.	5.	6.	7.	8.
Carbon	0.09	0.10	0.15	0.10	0.10	0.15	0.44	0.62
Silicon	trace	trace	0.018	trace	0.09	0.018	0.028	0.06
Sulphur	,,	0.022	0.019	0.035	0.03	0.092	0.126	0.074
Phosphorus	0.012	0.045	0.058	0.034	0.218	0.077	0.103	0.051
Manganese	0.06	0.03	0.234	0.324	0.234	0.72	1.296	1.584
Copper	trace	trace	trace	trace	0.015	trace	trace	trace
Iron	99.69	99.70	99.44	99.60	99.11	98.74	98.20	97.41
Ohm mile at 60 deg. Fahr. ...	4546	4502	4820	5308	5974	6163	7468	8033
Specific resistance (microhms per cubic centimetre at 0 deg. Cent.)	9.65	9.60	10.2	11.3	12.7	13.1	15.9	17.1
Specific resistance in microhms per cubic inch at 0 deg. Cent. ...	3.80	3.78	4.02	4.45	5.00	5.15	6.25	6.75
Resistance wire 1 ft. long and .001 in. in diameter at 0 deg. Cent.	57.9	57.5	61.2	67.7	76.2	78.5	95.5	103.0

No. 1. Swedish charcoal iron, very soft and pure.
,, 2. ,, ,, good for P. O. specification.
,, 3. ,, ,, not suited for P.O. specification.
No. 4. Swedish Siemens-Martin steel 0.10 carbon.
,, 5. Best puddled iron.
,, 6. Bessemer steel, special soft quality.
,, 7. ,, ,, hard quality.
,, 8. Best cast steel.

Although prepared in connection with telegraph and telephone work, it is of much significance to transformer builders, and points to the desirability of using as impure iron as can, by annealing, have its hysteresis loss reduced to a low value, since the higher specific resistance will proportionately decrease the eddy current loss. Such comparatively impure iron will also be nearly free from deterioration through prolonged heating. Of course its lower melting point renders it somewhat troublesome, owing to the plates tending to stick together when heated to a sufficiently high temperature to secure good results from annealing. Transformer builders in this country have generally used iron of some such quality as that of sample No. 1, and have been much troubled by "ageing." Most transformers in America have been built from material whose chemical composition is more like Samples 4, 5 and 6, and the transformers have been very free from "ageing." At least .4 per cent. of manganese should be present, owing to its property of raising the specific resistance.

Reference should here be made to a paper by M. H. Le Chatelier,

read before l'Académie des Sciences, June 13th, 1898, in which is given very useful data regarding the influence of varying percentages of carbon, silicon, manganese, nickel, and other elements, upon the electrical resistance of steels. The results relating to the influence of varying percentages of carbon, silicon and manganese are of especial importance, and are consequently reproduced in the following Tables:

TABLE VIII.—INFLUENCE OF CARBON

Specific Resistance in Microhms per Centimetre Cube.	Composition. C.	Mn.	Si.
10	0.06	0.13	0.05
12.5	0.20	0.15	0.08
14	0.49	0.24	0.05
16	0.84	0.24	0.13
18	1.21	0.21	0.11
18.4	1.40	0.14	0.09
19	1.61	0.13	0.08

TABLE IX.—INFLUENCE OF SILICON

Resistance in Microhms per Centimetre Cube.	Composition. C.	Si.
12.5	0.2	0.1
38.5	0.2	2.6
15.8	0.8	0.1
26.5	0.8	0.7
33.5	0.8	1.3
17.8	1.0	0.1
25.5	1.0	0.6
32.0	1.0	1.1

TABLE X.—INFLUENCE OF MANGANESE

Resistance in Microhms per Centimetre Cube.	Composition. C.	Mn.	Si.
17.8	0.9	0.24	0.1
22	0.9	0.95	0.1
24.5	1.2	0.83	0.2
40	1.2	1.8	0.9
66 magnetic 80 non-magnetic[1]	1.	13.	0.3

[1] In another paper by the same author are set forth results showing the influence of tempering upon the electric resistance of steel. *Comptes Rendus de l'Académie des Sciences*, June 20th, 1898.

Insulating Materials

The insulating materials used in dynamo construction vary greatly, according to the method of use and the conditions to be withstood. The insulation in one part of a dynamo may be subjected to high electrical pressures at moderate temperatures; in another part to high temperatures and moderate electrical pressures; in still another part to severe mechanical strains. No one material in any marked degree possesses all the qualities required.

Mica, either composite or solid, has been very largely used on account of its extremely high insulating qualities, its property of withstanding high temperatures without deterioration, and its freedom from the absorption of moisture. In the construction of commutators mica is invaluable. The use of mica, however, is restricted, on account of its lack of flexibility.

Moulded mica, *i.e.*, mica made of numerous small pieces cemented together, and formed while hot, has been used to insulate armature coils as well as commutators. Its use, however, has not been entirely satisfactory, on account of its brittleness.

Composite sheets of mica, alternating with sheets of paper specially prepared so as to be moisture-proof, have been found highly suitable for the insulation of armature and field-magnet coils. The following Table shows roughly the electrical properties of composite sheets of white mica :—

Table XI

Thickness.	Puncturing Voltage.
0.005	3,600 to 5,860
0.007	7,800 „ 10,800
0.009	8,800 „ 11,400
0.011	11,600 „ 14,600

The other materials that have been found more or less satisfactory, according to method of preparation and use, are linen soaked with linseed oil and dried; shellaced linen, which is a better insulator than oiled linen, but liable to be irregular in quality and brittle; oiled bond-paper, which is fairly satisfactory when baked; "press board," which shows good qualities, and has been used with satisfaction to insulate field-magnet coils.

Where linseed oil is to be employed, the material should be thoroughly dried before applying the oil.

Red and white vulcanised fibres are made by chemically treating paper fibre. They have been used as insulators with varying success, the main objection to them being their decidedly poor mechanical qualities, so far as warping and shrinking are concerned. This is due to their readiness to absorb moisture from the air. Baking improves the insulating qualities, but renders the substance brittle. Whenever it is necessary to use this material, it should be thoroughly painted to render it waterproof. The insulating quality varies according to the thickness, but good vulcanised fibre should withstand 10,000 volts in thicknesses varying from $\frac{1}{8}$ in. to 1 in., this puncturing voltage not increasing with the thickness, owing to the increased difficulty of thoroughly drying the inner part of the thick sheets.

Sheet leatheroid possesses substantially the same qualities, and is made according to the same processes as vulcanised fibre. A thickness in this material of $\frac{1}{64}$ in. should safely withstand 5000 volts, and should have a tensile strength of 5000 lb. per square inch.

TABLE XII.—TESTS ON SHEETS OF LEATHEROID

Thickness.	Insulation Strength.	
	Total Volts.	Volts per Mil.
in.		
$\frac{1}{64}$	5,000	320
$\frac{1}{32}$	8,000	256
$\frac{3}{64}$	12,000	256
$\frac{1}{16}$	15,000	240
$\frac{1}{8}$	15,000	120
$\frac{3}{16}$	6,000	32
$\frac{1}{4}$	6,000	24

With such materials as vulcanised fibre and sheet leatheroid, increase in thickness is not necessarily accompanied by increased insulation resistance, owing to the difficulty of obtaining uniformity throughout the thickness of the sheet. This is well shown in the tests of leatheroid sheets of various thicknesses, given in the preceding Table.

Rubber should never be used in any form in dynamo-electric machinery, as it deteriorates rapidly.

Slate is used for the insulation of the terminals of dynamos, &c. Ordinarily good slate will, when baked, withstand about 5000 volts per inch in thickness.

The chief objection to slate is its hygroscopic quality, and it requires to be kept thoroughly dry; otherwise, even at very moderate voltages, considerable leakage will take place. Where practicable, it is desirable to boil it in paraffin until it is thoroughly impregnated.

Slate is, moreover, often permeated with metallic veins, when it is quite useless as an insulator. But even when permeated with metallic veins, its mechanical and fireproof properties make it useful for switchboard and terminal-board work, in which case it is re-enforced by ebonite bushings.

Marble has the same faults as slate, though to a less extent.

Kiln-dried maple and other woods are frequently used, and will stand from 10,000 to 20,000 volts per inch in thickness.

The varnishes used for electrical purposes should, in addition to other insulating qualities, withstand baking; they should be waterproof, and not be subject to the action of oils. Further, they should not be liable to crack or to pulverise with time. Of the varnishes commonly used, shellac is one of the most useful. There are many insulating varnishes on the market, such as clear Sterling Varnish, Black Plastic Sterling Varnish, Armalac, and innumerable other brands.

One of the special insulating materials readily obtainable that has been found to be of considerable value is that known as "vulcabeston," which will withstand as high as 315 deg. Cent. with apparently no deterioration. This material is a compound of asbestos and rubber, the greater proportion being asbestos. Vulcabeston, ordinarily good, will withstand 10,000 volts per ½ in. of thickness.

As results of tests,[1] the following approximate values may be taken:—

Red press-board, .03 in. thick, should stand 10,000 volts. It should bend to a radius of five times its thickness, and should have a tensile strength along the grain of 6000 lb. per square inch.

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[1] See also R. T. Glazebrook, National Physical Laboratory, "Recent Researches and Future Work," *Electrician*, September 2nd, 1904.

Red rope paper, .01 in. thick, having a tensile strength along the grain of 50 lb. per inch of width, should stand 1000 volts.

Manilla paper, .003 in. thick, and having a tensile strength along the grain of 200 lb. per inch of width, should stand 400 volts.

TESTS ON OILED FABRICS

Oiled cambric	.007 in.	thick	stood from	2500 to 4500	volts.
„ cotton	.003	„	„	6300 „ 7000	„
„ paper	.004	„	„	3400 „ 4800	„
„ „	.010	„	5000 volts.		

A number of composite insulations are in use, consisting generally of split mica strips pasted with shellac on to sheets of some other material. The principal ones are:—

1. Insulation consisting of two sheets of .005 in. thick red paper, with one thickness of mica between them, the whole being shellaced together into a compound insulation .015 in. thick. This stands on the average 3,400 volts.

2. Combined mica and bond-paper of a thickness of .009 in. had a breaking strength of from 2000 to 3000 volts.

3. Composition of mica and canvas. Mica strips are pasted together with shellac on to a sheet of canvas, and covered with another sheet of canvas shellaced on. The mica pieces are split to be of approximately the same thickness—about .002 in.—and lapped over each other for half their width, and about $\frac{1}{8}$ in. beyond, so as to insure a double thickness of mica at every point. Each row of strips is lapped over the preceding row about $\frac{1}{2}$ in.

The sheets thus prepared are hung up and baked for twenty-four hours before use. The total thickness should be taken at about .048 in., using canvas .013 in. This will stand about 3000 R.M.S. volts.

4. Composition of mica and longcloth, made up with shellac in the same manner as the preceding material.

5. White cartridge paper shellaced on both sides, and baked for twelve hours at 60 deg. Cent. The total thickness is .012 in., and it will stand about 1500 volts per layer.

It will doubtless have been observed that the quantitative results quoted for various materials are not at all consistent. This is probably in part due to the different conditions of test, such as whether tested by continuous or alternating current; and if by alternating current the form

factor and periodicity would affect the results, and it should have been stated whether maximum or effective (R.M.S.) voltage was referred to. Continuous application of the voltage will, furthermore, often effect a breakdown in samples which resist the strain for a short interval.[1] It is also of especial importance that the material should have been thoroughly dried prior to testing; though on the other hand, if this is accomplished by baking, as would generally be the case, the temperature to which it is subjected may permanently affect the material. It thus appears that to be thoroughly valuable, every detail regarding the accompanying conditions and the method of test should be stated in connection with the results.

The importance of these points has only gradually come to be appreciated, and the preceding results are given for what they are worth. It is true that some tests have been made which are more useful and instructive, and various materials are being investigated exhaustively as rapidly as practicable. Such tests are necessarily elaborate and expensive and tedious to carry out, but it is believed that no simple method will give a good working knowledge of the insulating properties of the material.

TABLE XIII.—SUMMARY OF QUALITY OF INSULATING MATERIALS

—	Electrical.	Thermal.	Mechanical.	Hygroscopic.
Mica	Excellent	Excellent	Poor	Excellent
Hard rubber	„	Poor	Good	Fair
Slate	Very poor	Good	„	Poor
Marble	Good	„	„	„
Vulcabeston	Fair	Excellent	„	Good
Asbestos	Good	„	Poor	„
Vulcanised fibre	„	Good	„	Poor
Oiled linen	Excellent	Fair	Fair	Fair
Shellac'd linen	Good	„	Poor	Poor

EFFECT OF TEMPERATURE UPON INSULATION RESISTANCE

The resistance of insulating materials decreases very rapidly as the temperature increases, except in so far as the high temperature acts to expel moisture. Governed by these considerations, it appears that the apparatus should, so far as relates to its insulation, be run at a sufficiently high temperature to thoroughly free its insulation from moisture. The great extent of these changes in insulation resistance is very well shown in the accompanying curve (Fig. 41, opposite) taken from an investigation by

[1] See F. O. Blackwell, "Testing of Insulators," *Transactions*, American Institute of Electrical Engineers, vol xx., pages 421 to 425, April 1903.

Messrs. Sever, Monell and Perry.[1] It shows for the case of a sample of plain cotton duck, the improvement in insulation due to the expulsion of moisture on increasing the temperature, and also the subsequent deterioration of the insulation at higher temperatures.

Description of Insulation Testing Methods for Factories

The subject of testing insulating materials can be approached in two ways, having regard either to the insulation resistance or to the disruptive strength. Messrs. Sever, Monell and Perry, in the tests already alluded

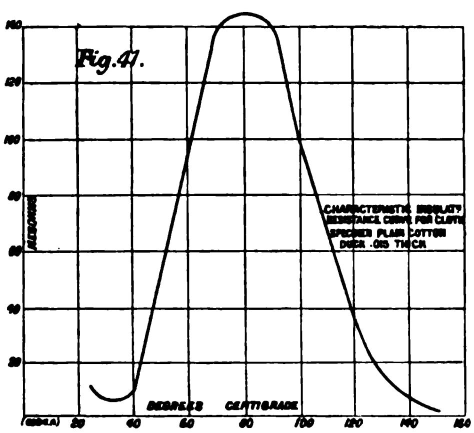
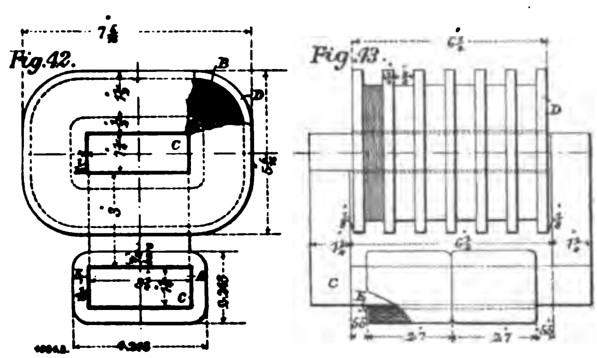


Fig. 41. Insulation Resistance Curve for Cloth



Figs. 42 and 43. Transformer for Insulation Tests

to, measured the former, but for practical purposes the latter is often preferable.

Various methods of testing insulating materials have been devised from time to time; but after many experiments on different lines the following has been evolved, and has been found very suitable for investigations in factory work. The apparatus required consists of:—

1. A special step-up transformer for obtaining the high potential from the ordinary alternating current low potential circuits. The design of this transformer is illustrated in Figs. 42 and 43, which are fully dimensioned.

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[1] "Effect of Temperature on Insulating Materials," American Institute of Electrical Engineers, May 20th, 1896. Also Elihu Thomson, *Transactions*, American Institute of Electrical Engineers, vol. xiv., page 265, 1897. Also C. E. Farrington, "Defective Machine Insulation," Franklin Institute, March 12th, 1903. Also Max von Recklinghausen, American Electro-Chemical Society, April 16th, 1903.

2. A water rheostat for regulating the current in the primary of the transformer. This consists of a glass jar, containing two copper plates immersed in water, the position of the upper one being adjustable.

3. A Kelvin electrostatic voltmeter, of the vertical pattern, for measuring the effective voltage on the secondary of the transformer.

4. A testing board for holding the sample to be tested. This, as shown in Fig. 44, is formed of two brass discs $\frac{1}{8}$ in. thick and $1\frac{1}{2}$ in. in diameter, the inside edges of which are rounded off to prevent an excess of intensity at these points. These are pressed together against the sample by two brass strips, which also serve to apply the voltage to the discs. The pressure between the discs is just enough to hold the sample firmly.

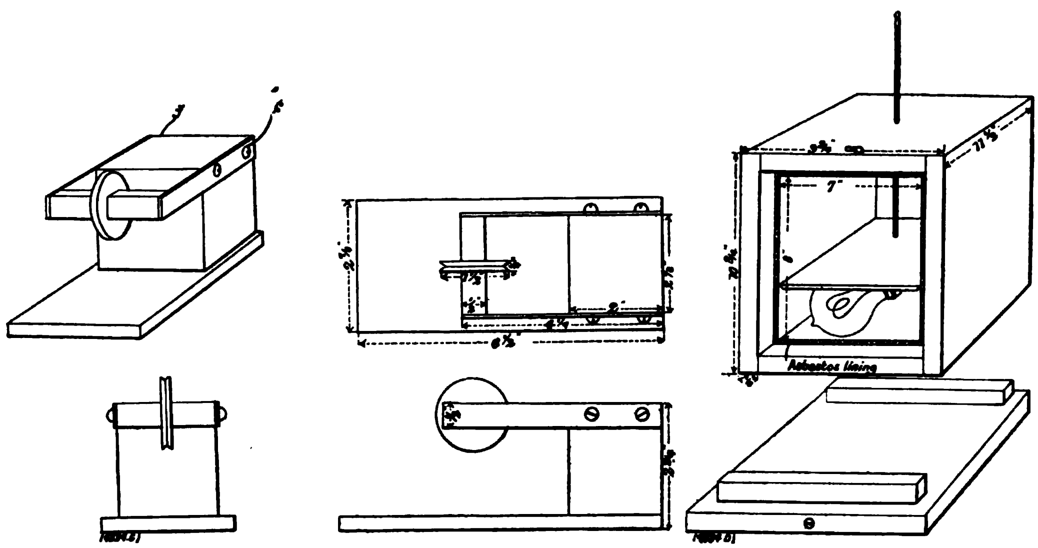


FIG. 44. APPARATUS FOR INSULATION TESTS

5. An oven for keeping the sample at the required temperature. It consists of a wooden box containing a tin case. There should be an inch clearance between the two, which should be tightly filled with asbestos packing all round, except at the front where the doors are. The tin case is divided horizontally by a shelf, which supports the testing board, while beneath is an incandescent lamp for heating the oven. Holes are drilled at the back to admit the high potential leads and lamp leads, and there is a hole in the top to admit a thermometer.

Adjustment of the temperature is made by having a resistance in series with the lamp, the amount of which can be adjusted till enough heat is generated to keep the temperature at the required value.

Description of Step-up Transformer

Core.—The core is of the single magnetic circuit type, and is built up of iron punchings $1\frac{1}{4}$ in. by $7\frac{3}{4}$ in., and $1\frac{1}{4}$ in. by $4\frac{1}{4}$ in., for sides and ends respectively, and .014 in. thick. Every other plate is japanned, and the total depth of punchings is $3\frac{1}{4}$ in., giving with an allowance of 10 per cent. for lost space, a net depth of iron of 2.92 in., and a net sectional area of 3.65 square inches. With an impressed E.M.F. of form factor = 1.25, the density is 36.4 kilolines per square inch.

The primary and secondary coils are wound on opposite sides of the core on the longer legs.

Primary Coils.—The primary consists of two coils form-wound, and these were slipped into place side by side. The conductor is No. 13 S.W.G. bare = .092 in. in diameter. Over the double cotton covering it measures .103 in., the cross-section of copper being .0066 square inch. Each coil consists of 75 turns in three layers, giving a total of 150 primary turns.

Secondary Coils.—The secondary is wound in six sections on a wooden reel, with flanges to separate the sections, as shown in Figs. 42 and 43. The conductor is No. 33 S.W.G. bare, .010 in. in diameter. Over the double silk covering it measures .014 in., the cross-section of copper being .000079 square inch. Each coil consists of 1,600 turns, giving a total of 9600 secondary turns.

Insulation.—The primary coils are wrapped with a layer of rolled tape (white webbing) 1 in., by .018 in., half lapped and shellac'd before being put on the core; they are slipped over a layer of "mica-canvas" on the leg. The secondary coils are wound direct on the wooden reel, which is shellac'd; they are covered outside with two or three layers of black tape (1 in. by .009 in.), shellac'd.

Advantage of this Type for Insulation Tests.—By having the primary and secondary on different legs, the advantage is gained that, even on short circuit, no great flow of current occurs, because of the magnetic leakage.

Connection Boards.—The transformer is mounted on a teak board, on which are also placed the secondary connection posts, as shown in Fig. 45, page 52. The primary leads are brought to another teak board, which is for convenience mounted on the top of the transformer. This board is fitted with fuses.

A number of samples may be tested simultaneously by connecting the

testing boards in parallel, as shown in the diagram of connections given in Fig. 45, page 52. A is a single-pole switch in the main secondary circuit, and B, B, B are single-pole switches in the five branches.

The method of test is as follows: A number of samples 4 in. square are cut from the material to be tested, and are well shuffled together. Five samples are taken at random, placed between the clips of the testing boards within the ovens, and brought to the temperature at which the test is to be made. They should be left at this temperature for half an hour before test.

The apparatus may, of course, be modified to suit special requirements; but, as described, it has been used and found suitable for investigations on the disruptive voltage of various materials.

As an example of such an investigation, we give one in Table XIV. that was made to determine the effect of different durations of strain and different temperatures on the disruptive strength of a composite insulation known as mica-canvas.

Two hundred samples, measuring 4 in. by 4 in., were cut and well shuffled together, in order to eliminate variations of different sheets. Before test, all samples were baked for at least twenty-four hours at 60 deg. Cent.

Method of Test

Five samples were placed between the clips of the testing boards, and the voltage on the secondary adjusted by the water rheostat to 2000 volts, as indicated by a static voltmeter. Switch A was open and switches B, B, B closed (Fig 45). Switch A was now closed for five seconds, and if no sample broke down the voltage was raised to 3000, and Switch A again closed for five seconds. This application of the voltage is practically only momentary, as the capacity current of the samples brings down the voltage slightly because of magnetic leakage in the transformer, five seconds not being a long enough interval to admit of re-adjusting the pressure to the desired value.

When any sample broke down, as indicated by the voltmeter needle dropping back to zero, it was disconnected from the circuit by its switch, B; it being easy to determine which sample had broken down by lifting switches B, B, B, one by one, till one of them drew out an arc.

The remaining samples were then subjected to the next higher voltage, and so on until all five samples had broken down.

A series of four tests, as below, were taken, making a total of twenty samples tested under the same conditions.

TABLE XIV.—INSULATION TESTS; MICA-CANVAS

Effective Voltage Impressed.	Duration 5 Seconds. Number of Samples Unpierced.					Duration 10 Minutes. Number of Samples Unpierced.					Duration 30 Minutes. Number of Samples Unpierced.				
					per cent.					per cent.					per cent.
	Temperature 25 *deg. Cent.*														
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
4000	5	5	4	5	95	5	5	5	5	100	5	3	3	3	70
4500	5	5	4	5	95	4	2	5	5	80	5	2	2	3	60
5000	4	5	4	5	90	1	1	3	3	40	4	1	1	1	35
5500	4	4	3	5	80	0	0	3	2	25	2	0	0	0	10
6000	3	2	2	3	50	0	0	2	1	15	2	0	0	0	10
6500	3	1	2	1	35	0	0	2	0	10	1	0	0	0	5
7000	1	0	1	0	10	0	0	1	0	5	1	0	0	0	5
7500	0	0	1	0	5	0	0	0	0	0	1	0	0	0	5
8000	0	0	1	0	5	0	0	0	0	0	1	0	0	0	5
	Temperature 60 *deg. Cent.*														
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
4000	5	3	5	4	85	4	2	2	5	65	1	4	2	4	55
4500	5	3	5	3	80	1	2	2	3	40	1	3	2	4	50
5000	3	2	5	2	60	1	1	2	2	30	0	3	1	4	40
5500	1	2	5	1	45	0	0	1	0	5	0	3	0	2	25
6000	0	0	5	1	30	0	0	0	0	0	0	1	0	1	10
6500	0	0	0	0	0	0	0	0	0	0	0	0	0	8	5
7000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7500															
8000															
	Temperature 100 *deg. Cent.*														
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	4	5	5	100	5	5	5	5	100
4000	4	5	5	4	90	4	4	5	5	90	2	5	0	4	60
4500	4	5	4	4	85	3	3	3	3	60	1	3	0	2	35
5000	2	5	3	4	70	2	2	3	2	45	1	0	0	0	5
5500	1	5	2	3	55	1	1	2	2	30	0	0	0	0	0
6000	1	3	1	2	35	1	1	1	0	15					
6500	0	1	0	1	10	1	0	0	0	5					
7000	0	0	0	0	0	0	0	0	0	0					
7500															

A set of twenty samples was tested with the impressed voltage kept constant for ten minutes, and another set in which it was kept constant for thirty minutes.

A complete series of tests was made under the above three conditions—at three different temperatures—25 deg. Cent., 60 deg. Cent., and 100 deg. Cent. The samples were left in ovens for at least half

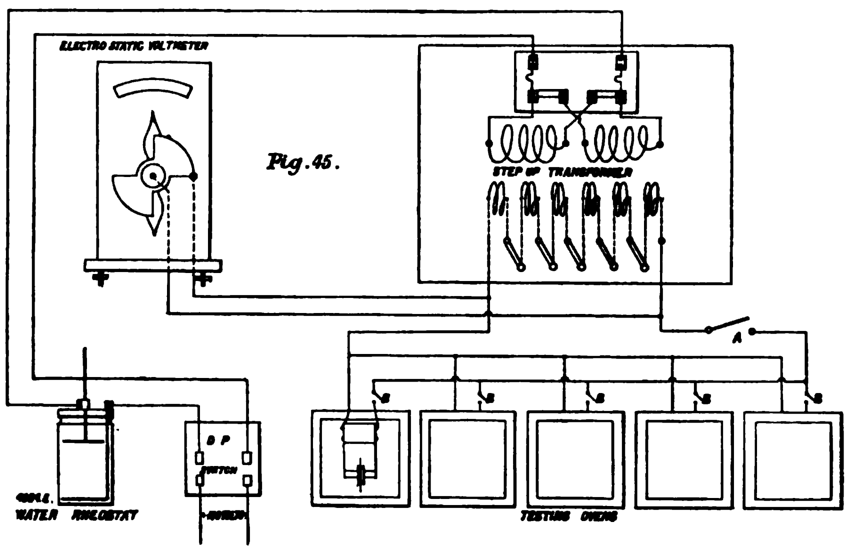
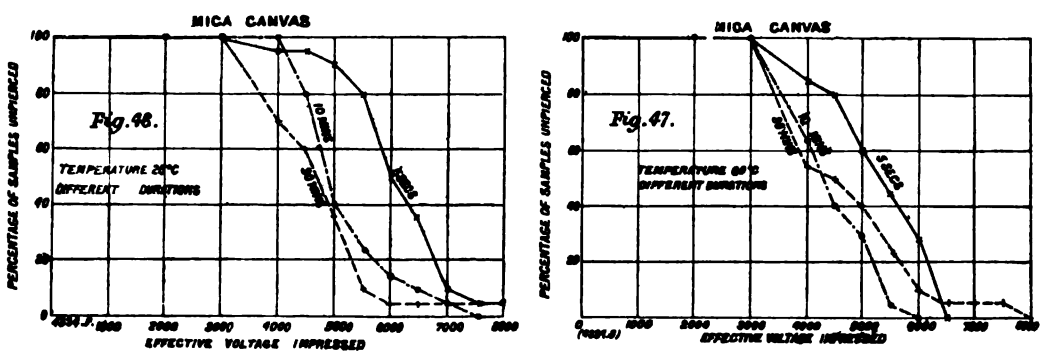


FIG. 45. CIRCUIT CONNECTIONS FOR INSULATION TESTS



FIGS. 46 AND 47. INSULATION CURVES FOR "MICA CANVAS"

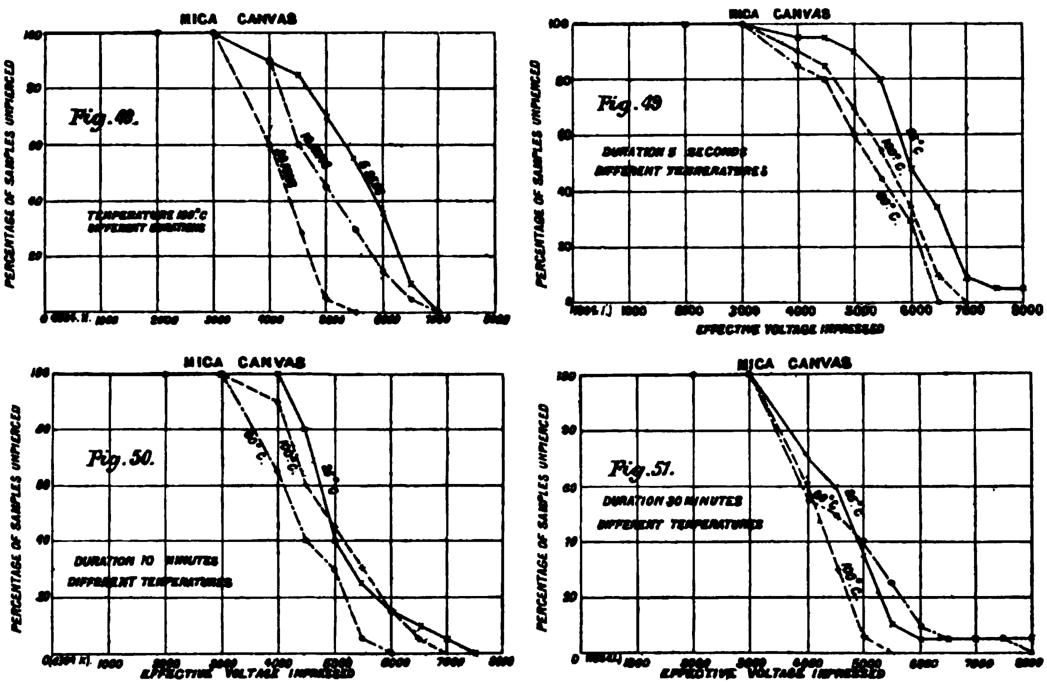
an hour, at approximately the right temperature, before being tested. The temperature during test did not vary more than 10 per cent.

The results of these tests are given in the Table on the preceding page, and they are plotted as curves in Figs. 46 to 51, the effective (R.M.S.) voltage impressed as abscissæ, and the percentage of samples not broken down at that voltage as ordinates. In Figs. 46, 47, and 48, curves are plotted for same temperatures and different durations, while

in Figs. 49, 50, and 51 they are plotted for different temperatures for the same duration.

As the form of the electromotive force wave would affect the results, and as it was impracticable to keep account of the same, the current being supplied by Thomson-Houston and Brush alternators running in parallel and at various loads, the effects were eliminated as much as possible by making tests on different sets of samples on different days.

It is evident from the results obtained that 3000 R.M.S. volts

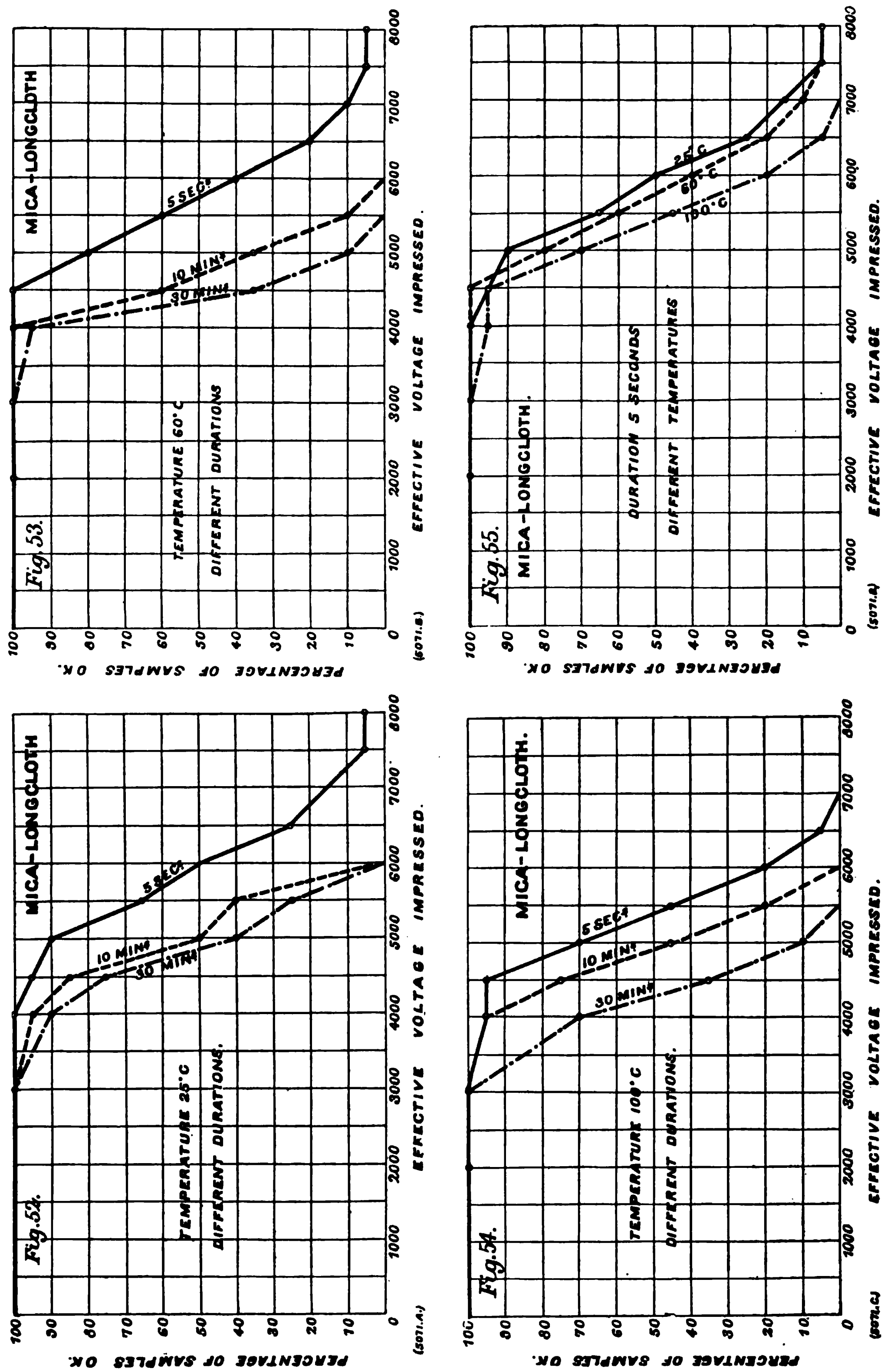


FIGS. 48 TO 51. INSULATION CURVES FOR "MICA-CANVAS"

is the limit of safe-working voltage of this material under all conditions tried.

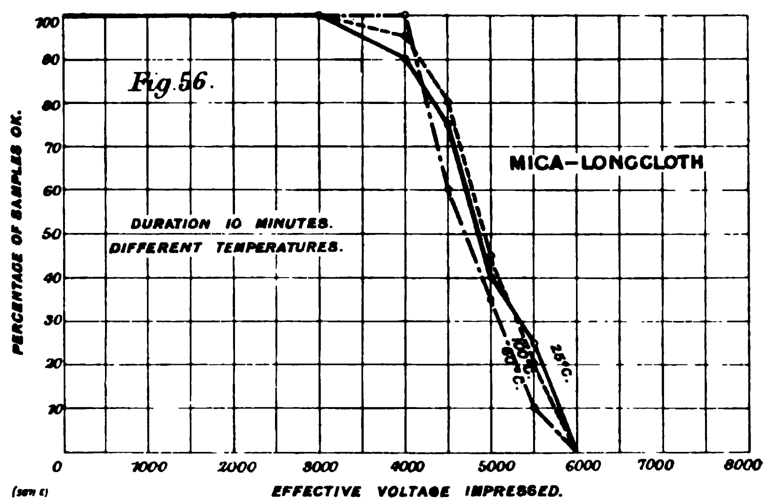
It would also appear from curves in Figs. 46, 47, and 48, that with the momentary application of the voltage, the material does not have time to get so strained as for a longer duration of the applied voltage, and that between the ten-minute and thirty-minute durations the difference is not so marked.

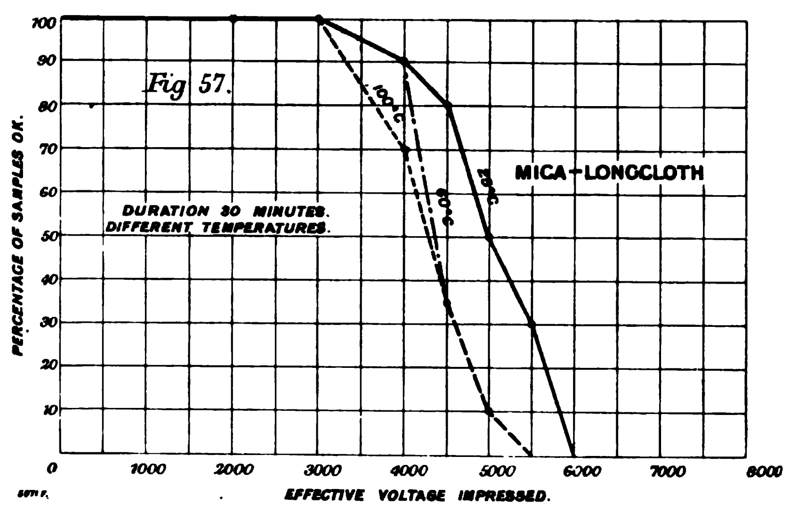
From curves in Figs. 49, 50, and 51, it seems that in the case of this material the temperature does not have much effect on the disruptive voltage, although at 60 deg. and 100 deg. the shellac becomes softened, and the sample may be bent back on itself without cracking.



FIGS. 52 TO 55. INSULATION CURVES FOR "MICA-LONGCLOTH"

A corresponding set of tests was made on material called "mica-long-cloth," which differed from the "mica-canvas" only in the nature of the cloth upon which the mica was mounted. The "long-cloth" is an inexpensive grade of linen serving merely as a structure upon which to build the mica. The mode of manufacture is the same as that of "mica-canvas," except





FIGS. 56 AND 57. INSULATION CURVES FOR "MICA-LONGCLOTH"

that the sheets of "long-cloth" are first impregnated with shellac and then dried. The mica is then put on in the same manner as with the "mica-canvas." The "long-cloth" is .0052 in. thick, and the mica varies from .001 in. to .009 in., but averages .002 in. The total thickness of the "mica long-cloth" completed, averages .025 in. This includes two sheets of "mica long-cloth," with interposed mica, the mica having everywhere at

least a double thickness. When made up, the sheets were placed for three or four hours in an oven at 60 deg. Cent. The sheets were then cut up into samples measuring 4 in. by 4 in., and were again baked for twenty-four hours before testing.

TABLE XV.—INSULATION TESTS: MICA-LONGCLOTH

Temperature, 25 *deg. Cent.*

Effective Voltage Impressed.	Duration, 5 Seconds.					Duration, 10 Minutes.					Duration, 30 Minutes.				
	Number of Samples O K.					Number of Samples O K.					Number of Samples O K.				
					Per Cent.					Per Cent.					Per Cent.
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
4000	5	5	5	5	100	4	4	5	5	90	5	5	4	5	95
4500	4	5	5	5	95	4	3	3	5	75	4	5	3	5	85
5000	4	5	5	4	90	3	2	2	2	40	2	1	3	4	50
5500	3	2	5	3	65	2	1	0	1	25	0	0	2	4	30
6000	2	2	4	2	50	0	0	0	0	0	0	0	0	0	0
6500	0	2	2	1	25	0	0	0	0	0	0	0	0	0	0
7000	0	2	1	0	15	0	0	0	0	0	0	0	0	0	0
7500	0	1	0	0	5	0	0	0	0	0	0	0	0	0	0
8000	0	1	0	0	5	0	0	0	0	0	0	0	0	0	0
Temperature, 60 *deg. Cent.*															
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
4000	5	5	5	5	100	5	5	5	5	100	4	5	5	5	95
4500	5	5	5	5	100	3	3	1	5	60	2	2	1	2	35
5000	4	4	3	5	80	1	2	1	3	35	0	2	0	0	10
5500	3	4	2	3	60	0	0	0	2	10	0	0	0	0	0
6000	1	3	2	2	40	0	0	0	0	0	0	0	0	0	0
6500	1	2	0	1	20	0	0	0	0	0	0	0	0	0	0
7000	1	1	0	0	10	0	0	0	0	0	0	0	0	0	0
7500	0	1	0	0	5	0	0	0	0	0	0	0	0	0	0
8000	0	1	0	0	5	0	0	0	0	0	0	0	0	0	0
Temperature, 100 *deg. Cent.*															
2000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
4000	5	4	5	5	95	5	5	4	5	95	5	3	3	3	70
4500	5	4	5	5	95	4	4	2	5	75	4	0	3	0	35
5000	4	3	4	3	70	3	3	2	3	45	1	0	1	0	10
5500	3	2	3	1	45	2	2	2	0	20	0	0	0	0	0
6000	1	1	1	1	20	0	0	0	0	0	0	0	0	0	0
6500	0	3	0	1	5	0	0	0	0	0	0	0	0	0	0
7000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The results which are given in Table XV. and plotted as curves, show much the same character as those for "mica-canvas," the limit of safe working being about 3,000 R.M.S. volts as before. The results as plotted

in the curves support the former conclusion, that with five seconds duration of the application of the voltage, the material is not so much strained as by longer applications. As before, also, the temperature does not appear to affect the disruptive voltage.

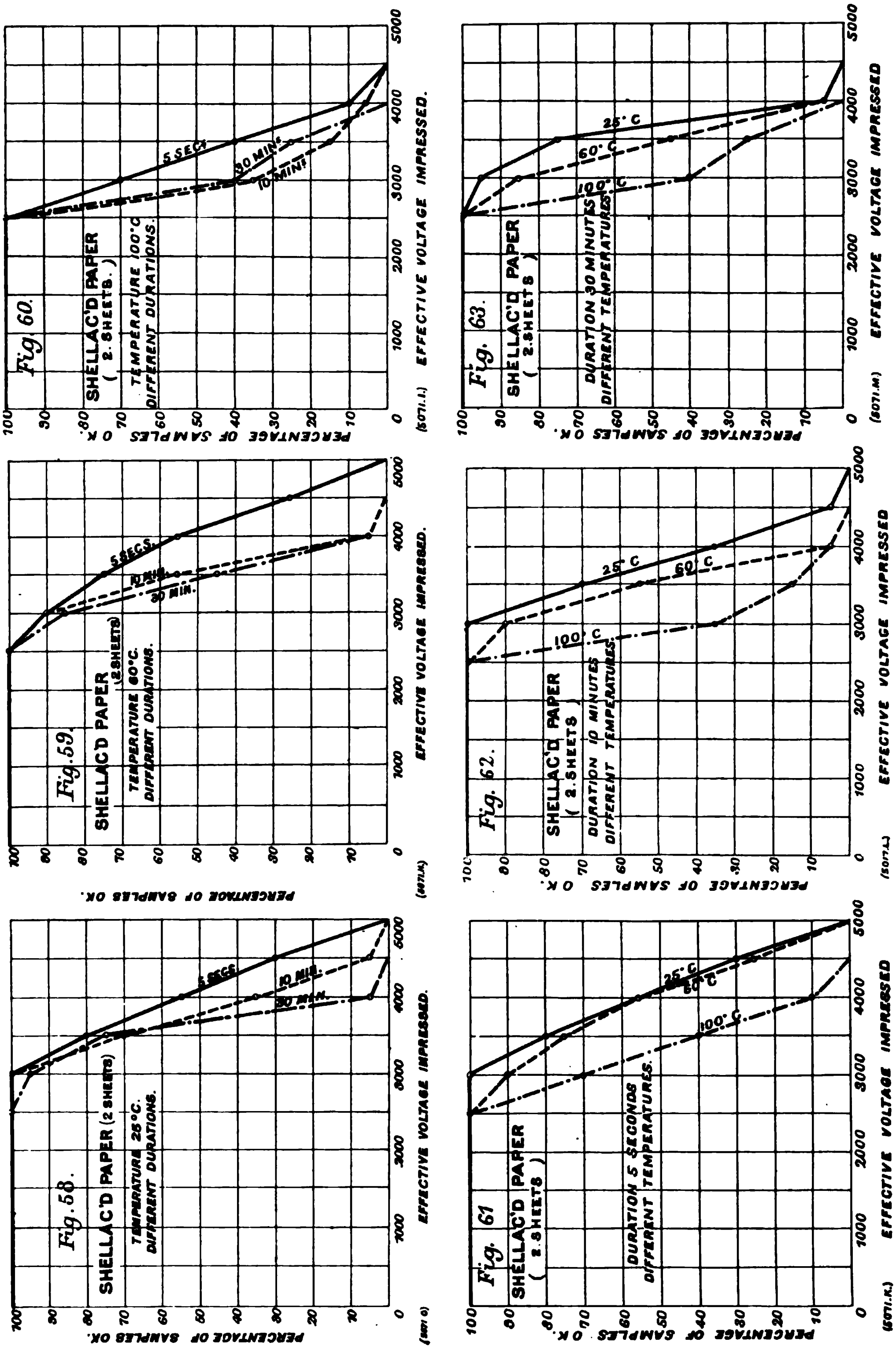
These tests show the material to be quite as good electrically as "mica-canvas," nothing being gained by the extra thickness of the latter. The "mica-canvas" and the "mica long-cloth" had the same thickness of mica, but the canvas is so much thicker than the "long-cloth" as to make the total thickness of the "mica-canvas" .048 in., as against a thickness of only .025 in. for the "mica long-cloth." The insulation strength is evidently due solely to the mica.

TABLE XVI.—INSULATION TESTS: SHELLAC'D PAPER (Two Sheets)

Temperature, 25 *deg. Cent.*

Effective Voltage Impressed.	Duration, 5 Seconds.					Duration, 10 Minutes.					Duration, 30 Minutes.				
	Number of Samples O K.				Per Cent.	Number of Samples O K.				Per Cent.	Number of Samples O K.				Per Cent.
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	4	5	100
3500	4	4	4	4	80	4	5	2	3	70	4	4	2	5	75
4000	3	2	3	3	55	3	2	1	1	35	0	1	0	0	5
4500	2	1	2	1	30	1	0	0	0	5	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature, 60 *deg. Cent.*															
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	4	5	4	5	90	5	3	5	5	90	4	4	4	5	85
3500	4	4	3	4	75	2	3	3	3	55	2	2	3	2	45
4000	2	3	3	3	55	1	0	0	0	5	0	0	0	1	5
4500	1	2	0	2	25	0	0	0	0	0	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature, 100 *deg. Cent.*															
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	3	3	4	4	70	2	2	2	2	35	1	3	2	2	44
3500	2	1	3	2	40	2	0	0	0	15	1	2	0	2	25
4000	0	0	1	1	10	1	0	0	0	5	0	0	0	0	0
4500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

In the following set of tests the same method of procedure was employed, the material in this case being so-called "Shellac'd Paper," which consists of cartridge paper about .010 in. thick, pasted with shellac on both sides and then thoroughly baked. The average thickness when finished is about .012 in. This material is often used as insulation between layers of the windings of transformers, in thicknesses of from one to three



FIGS. 58 TO 63. INSULATION CURVES FOR "SHELLAC'D PAPER"

sheets, according to the voltage per layer. It was found convenient to test two sheets of the material together, in order to bring the disruptive voltage within the range of the voltmeter. The use of two thicknesses also tended to produce more uniform results. As will be seen, the duration of the application of the voltage, and the temperature up to 100 deg. Cent., exert a slight but definite influence upon the results. But at 100 deg. Cent. the shellac becomes quite soft.

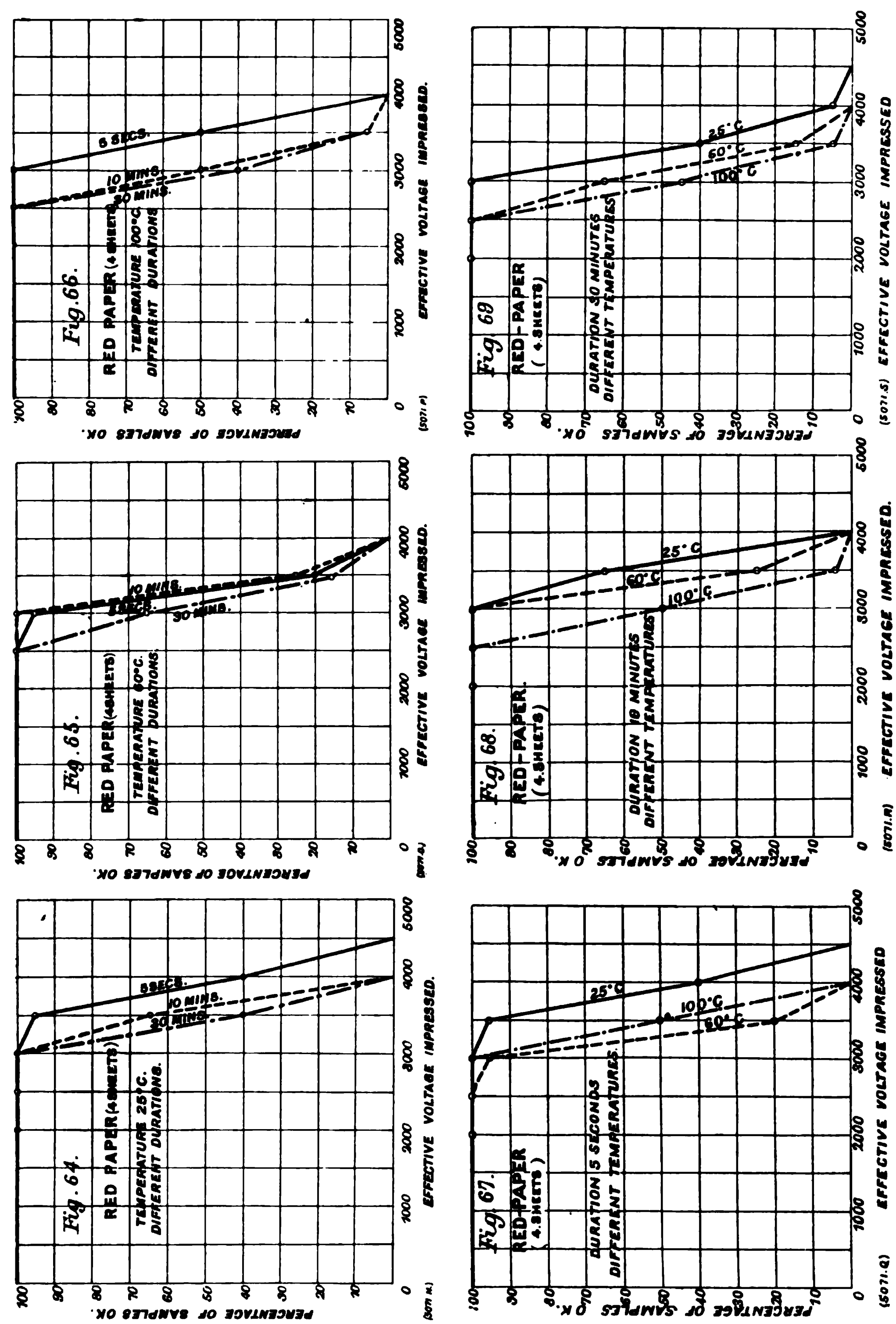
The tests show that this material withstands a little over 1000 R.M.S. volts per single sheet, although in employing it for construction, a factor of safety of two or three should be allowed under good conditions, and a still higher factor for the case of abrupt bends and other unfavourable conditions.

Further tests showed the disruptive strength of this material to be proportional to the number of sheets.

Curves (Figs. 64 to 69, page 60, and Table XVII.) are given of the results obtained in similar tests on a material known as "Red Paper." It is .0058 in. thick, of a fibrous nature, and mechanically strong; hence it is especially useful in conjunction with mica, to strengthen the latter.

TABLE XV II.—INSULATION TESTS: RED PAPER (Four Sheets)

Effective Voltage Impressed.	Duration 5 Seconds.					Duration 10 Minutes.					Duration 30 Minutes.				
	Number of Samples O K.					Number of Samples O K.					Number of Samples O K.				
					Per Cent.					Per Cent.					Per Cent.
Temperature, 25 deg. Cent.															
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3500	5	4	5	5	95	2	4	5	5	65	2	4	2	0	40
4000	4	0	1	3	40	0	0	0	0	0	1	0	0	0	0
4500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature, 60 deg. Cent.															
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	4	95	5	5	5	5	100	4	2	2	5	65
3500	0	1	2	2	20	3	1	1	0	25	0	1	1	1	15
4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Temperature, 100 deg. Cent.															
2500	5	5	5	5	100	5	5	5	5	100	5	5	5	5	100
3000	5	5	5	5	100	3	2	2	3	50	3	3	2	1	45
3500	2	3	2	3	50	1	0	0	0	5	0	1	0	0	5
4000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0



FIGS. 64 TO 69. INSULATION CURVES FOR "RED PAPER"

The method of test was the same as that employed in the case of the preceding set of tests on "Shellac'd Paper;" and for the reasons set forth in those tests, it was found in this case convenient to test four sheets of the material together.

An examination of the curves and Table will show that the limit of safe working is 2,500 R.M.S. volts for four sheets, or 625 volts for a single sheet, other tests having been made which showed the breakdown pressure to be proportional to the number of sheets.

It also appears from the curves, that "Red Paper" has a more uniform insulation strength than the materials previously tested. As in the case of "Shellac'd Paper," it showed weakening of the insulation at a temperature of 100 deg. Cent.

From tests such as the four sets just described, very definite conclusions may be drawn. For instance, if it were desired to use "mica-canvas" as the chief constituent of the main insulation of a 2000 volt transformer, which should withstand an 8,000 volt breakdown test, between primary and secondary, for one half hour, three layers of this composite insulation would be sufficient and would probably be inserted; though the chances would be in favour of its withstanding a 10,000 or 12,000 volt test if due attention is given to guarding against surface leakage, bending and cracking and bruising of insulation, and other such matters. A comparison with the tests on "mica-longcloth," would, however, show that a given insulation strength could be obtained with a much thinner layer.

There are on the market patented composite materials giving much better results. But they are expensive, and hence it is often impracticable to use them.

In designing electrical machinery, similar tests of all insulating material to be used should be at hand, together with details of their mechanical, thermal, and other properties, and reasonable factors of safety should be taken.

Armature coils are often insulated by serving them with linen or cotton tape wound on with half-lap. A customary thickness of tape is .007 in., and the coil is taped with a half over-lap, so that the total thickness of the insulation is .014 in. The coils are then dipped in some approved insulating varnish, and baked in an oven at a temperature of about 90 deg. Cent. These operations of taping, dipping, and drying, are repeated a number of times, until the required amount of insulation is

obtained. It has been found in practice that a coil treated in this manner, and with but three layers of .007-in. tape (wound with half over-lap), dipped in varnish twice after the first taping, once after the second, and twice after the third, *i.e.*, five total dippings, and thoroughly baked at 90 deg. cent. after each dipping in varnish, withstands a high potential test of 5,000 R.M.S. volts, which is considered sufficient for machines for not over 600 volts. Armature coils insulated in the above manner are generally placed in armature slots lined with an oil-treated cardboard of about .012 in. in thickness; but this contributes but little to the insulation strength, serving rather to protect the thin skin of varnish from abrasion when forcing the coil into the armature slot. In this treatment of the coils, great care must be taken to see that the taping be not more than one half over-lap, and that the varnish does not become too thick through evaporation of the solvent. All coils should be thoroughly dried and warmed before dipping, as the varnish will then penetrate farther into them. The slot parts of coils are dipped in hot paraffin and the slots lined with oil- or varnish-treated cardboard, to prevent abrasion of the insulations. The greatest care should be used in selecting insulating varnishes and compounds, as many of them have proved in practice to be worthless; a vegetable acid forming in the drying process, which corrodes the copper through the formation of acetates or formates of copper which in time lead to short-circuits in the coil. Some excellent preparations have their effectiveness impaired by unskilful handling. If, for instance, the first coat of the compound is not thoroughly dried, the residual moisture corrodes the copper and rots the insulations. By far the best method of drying is by the vacuum hot oven. By this method, the coils steam and sweat, and all moisture is sucked out. A vacuum oven, moreover, requires a much lower temperature, consequently less steam, and very much less time. Such an oven is almost a necessity where field spools have deep metal flanges, for in the ordinary oven, in such cases, the moisture simply cooks and steams, but does not come out. Cases have occurred where spools have been kept in an ordinary drying oven for ten days at a temperature of 90 deg. cent., and then the spools had to be further dried with a heavy current to sweat the moisture out. Field spools may be treated with tape and varnished in the same manner as armature coils, thus doing away with the needless metal flanges, and also saving space.

As further instances of taping and varnishing, may be cited the cases of some coils treated with the same kind of tape and varnish as

already described. In one case, a half over-lapped covering of .007 in. tape giving a total thickness of .014 in., had seven successive dippings and bakings, resulting in a total thickness of tape and varnish of .035 in. Coils thus insulated withstood 6,000 R.M.S. volts. An insulation suitable for withstanding 15,000 R.M.S. volts consists in taping four times with half over-lap, and giving each taping three coats of varnish, making in all eight layers of ·007-in. tape, and twelve layers of varnish. The total thickness of insulation was then about .09 in. The quality of tape, thickness of varnish, and care in applying and drying the latter, play an important part. One disadvantage of this method of insulating by taping and impregnating with varnish and baking, consists in the brittleness of the covering ; a coil thus treated should preferably be warmed before pressing it into place on the armature.

Other methods of treating coils, such as dipping the slot part in shellac and then pressing it in a steam-heated press form, thus baking the slot part hard and stiff, have the advantage of rendering the coils less liable to damage in being assembled on the armature, and also make them more uniform in thickness. Coils thus pressed are subsequently taped and dipped in the way already described. Coils may be treated in a vacuum, to a compound of tar and linseed oil, until they become completely impregnated. They are then forced into shape under high pressure. Coils thus prepared cannot be used in rotating armatures, as the centrifugal force tends to throw the compound out.

For further details of "The Insulation of Electric Machines," see the treatise under this title by H. W. Turner and H. M. Hobart (Whittaker, 1905). This treatise also contains a Chapter devoted to an extensive bibliography of the subject of insulating materials and methods.

While this work is in the press there has come to hand an advance copy of a very interesting paper by E. H. Rayner, entitled :—" Report on Temperature Experiments carried out at the National Physical Laboratory." This paper was read at the Institution of Electrical Engineers, on March 9th, 1905 ; it gives useful data on Press-spahn, Manila Paper, Excelsior Paper and Linen, Grey and Red Fibre, and other materials. The tests include comparisons at various temperatures and for various thicknesses. It is to be hoped, however, that the National Physical Laboratory will regard these tests as merely preliminary to far more comprehensive and precise tests.

ARMATURE WINDINGS

Continuous-Current Armature Windings

In the design of dynamo machines a primary consideration is with respect to the armature windings. Many types have been, and are, at present employed, but the large continuous-current generators now most extensively used for power and lighting purposes, as well as in the numerous other processes where electrical energy is being commercially utilised on a large scale, are constructed with some one selected from a comparatively small number of types of winding. Although the many other types may be more or less useful in particular cases, it will not be necessary for our present purpose to treat the less-used types.

The windings generally used may be sub-divided into two chief classes —one, in which the conductors are arranged on the external surface of a cylinder, so that each turn includes, as a maximum, the total magnetic flux from each pole, termed drum windings; the other, in which the conductors are arranged on and threaded through the interior of a cylinder, so that each turn includes as a maximum only one-half of the flux from each magnet pole; this is known as the Gramme, or ring winding.

One of the chief advantages of the Gramme winding is that the voltage between adjacent coils is only a small fraction of the total voltage, while in drum-wound armatures the voltage between adjacent armature coils is periodically equal to the total voltage generated by the armature. On account of this feature, Gramme windings are largely used in the armatures of arc-light dynamos, in which case the amount of space required for insulation would become excessive for drum windings. There is also the practical advantage that Gramme windings can be arranged so that each coil is independently replaceable.

Gramme-ring windings have been used with considerable success in large lighting generators, the advantage in this case being that the armature conductors are so designed that the radial ends of each turn at one side of the armature are used as a commutator; and with a given number of conductors on the external surface of the cylinder, the number of the commutator bars is twice as great as in the drum-wound armature—an important

feature in the generation of large currents. Having one commutator segment per turn, the choice of a sufficient number of turns keeps the voltage per commutator segment within desirably low limits. The use of a large number of turns in such cases, while permitting the voltage per commutator segment to be low, would entail high armature reaction, manifested by excessive demagnetisation and distortion, if the number of poles should be too small; but by the choice of a sufficiently large number of poles, the current per armature turn may be reduced to any desired extent. While it is necessary to limit the armature strength in this way, the cost

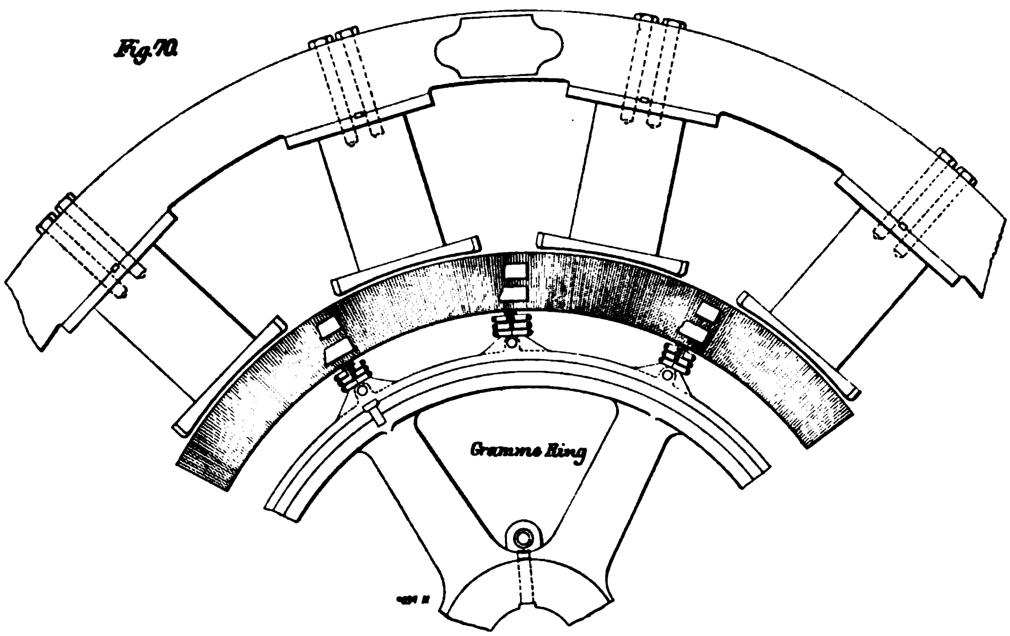


FIG. 70. GRAMME RING WINDING WITH LATERAL COMMUTATOR

of the machine is at the same time increased, so that commercial considerations impose a restriction.

Fig. 70 is an outline drawing of the armature and field of a 12-pole 400-kilowatt Gramme-ring lighting generator, of the type just described. Machines of this type have been extensively used in large central stations in America, and it is one of the most successful types that have ever been built.

In small machines where, instead of two-face conductors, there is often a coil of several turns between adjacent commutator segments, the Gramme ring is, on the score of mechanical convenience, inferior to the drum winding; since, in the case of the latter, the coils may be wound upon a form,

and assembled afterwards upon the armature core. This is only made practicable in the case of a Gramme ring, by temporarily removing a segment of the laminated core. This plan has obvious disadvantages.

These two practical classes of windings, Gramme ring and drum, may be subdivided, according to the method of interconnecting the conductors, into "two-circuit" and "multiple-circuit"[1] windings. In the two-circuit windings, independently of the number of poles, there are but two circuits through the armature from the negative to the positive brushes; in the multiple-circuit windings, there are as many circuits through the armature as there are poles.

Making comparison of these two sub-classes, it may be stated that in the two-circuit windings the number of conductors is, for the same voltage, only 2/N times the number that would be required with a multiple-circuit winding, N being the number of poles; hence a saving is effected in the labour of winding and in the space required for insulation. This last economy is frequently of great importance in small generators, either lessening the diameter of the armature or the depth of the air gap, and thereby considerably lessening the cost of material.

It has been stated that Gramme-ring armatures have the advantage that only a small fraction of the total voltage exists between adjacent coils. This is only true when the Gramme armature either has a multiple-circuit winding, or a certain particular type of two-circuit winding, known as the Andrews winding, *i.e.* the long-connection type of two-circuit Gramme-ring winding. This reservation having been made for the sake of accuracy, it is sufficient to state that multiple-circuit Gramme-ring windings are the only ones now used to any extent in machines of any considerable capacity; and, as already stated, these possess the advantage referred to, of having only a small fraction of the total voltage between adjacent coils.

Drum Windings

In the case of drum windings, it is obvious that all the connections from bar to bar must be made upon the rear and front ends exclusively; it not being practicable, as in the case of Gramme-ring windings, to bring connections through inside from back to front. From this it follows that the face conductors forming the two sides of any one coil must be situated in fields of opposite polarity; so that the electromotive forces generated in

[1] This term applies to single armature windings

the conductors composing the turns, by their passage through their respective fields, shall act in the same direction around the turns or coils.

Bipolar windings are, in some cases, used in machines of as much as 100 or even 200 kilowatts output; but it is now generally found desirable to employ multipolar generators even for comparatively small outputs. The chief reasons for this will be explained hereafter, in the section relating to the electro-magnetic limit of output.

Drum windings, like Gramme-ring windings, may be either multiple-circuit or two-circuit, requiring in the latter case, for a given voltage, only 2/N times as many conductors as in the former, and having the advantages inherent to this property. Owing to the relative peripheral position of successively connected conductors (in adjacent fields), two-circuit drum windings are analogous to the short-connection type, rather than to the long-connection type of two-circuit Gramme-ring windings. The multiple-circuit drum windings are quite analogous to the multiple-circuit Gramme-ring windings, the multiple-circuit drum possessing, however, the undesirable feature of full armature potential between neighbouring conductors; whereas one of the most valuable properties of the multiple-circuit Gramme-ring winding is that there is but a very small fraction of the total armature potential between adjacent conductors.

In Fig. 71, page 68, is given the diagram of a multiple-circuit drum winding. It is arranged according to a plan which has proved convenient for the study of drum windings. The radial lines represent the face conductors. The connecting lines at the inside represent the end connections at the commutator end, and those on the outside the end connections at the other end. The brushes are drawn inside the commutator for convenience. The arrowheads show the direction of the current through the armature, those without arrowheads (in other diagrams) being, at the position shown, short-circuited at the brushes. By tracing through the winding from the negative to the positive brushes, it will be found that the six paths through the armature are along the conductors, and in the order given in the six following lines :—

$$
- \left\{ \begin{array}{cccccccccc}
7 & 58 & 9 & 60 & 11 & 2 & 13 & 4 & 15 & 6 \\
56 & 5 & 54 & 3 & 52 & 1 & 50 & 59 & 48 & 57 \\
27 & 18 & 29 & 20 & 31 & 22 & 33 & 24 & 35 & 26 \\
16 & 25 & 14 & 23 & 12 & 21 & 10 & 19 & 8 & 17 \\
47 & 38 & 49 & 40 & 51 & 42 & 53 & 44 & 55 & 46 \\
36 & 45 & 34 & 43 & 32 & 41 & 30 & 39 & 21 & 37
\end{array} \right\} +
$$

In making the connections, each conductor at the front end is connected to the eleventh ahead of it; and at the back to the ninth behind

it. In other words, the front end pitch is 11, and the back end pitch is -9. In practically applying such a diagram, the conductors would generally be arranged with either one, two, or four conductors in each slot. Suppose there were two conductors per slot, one above the other; then the odd-numbered conductors could be considered to represent the upper conductors, the lower ones being represented by conductors with even numbers. In order that the end connections may be of the ordinary

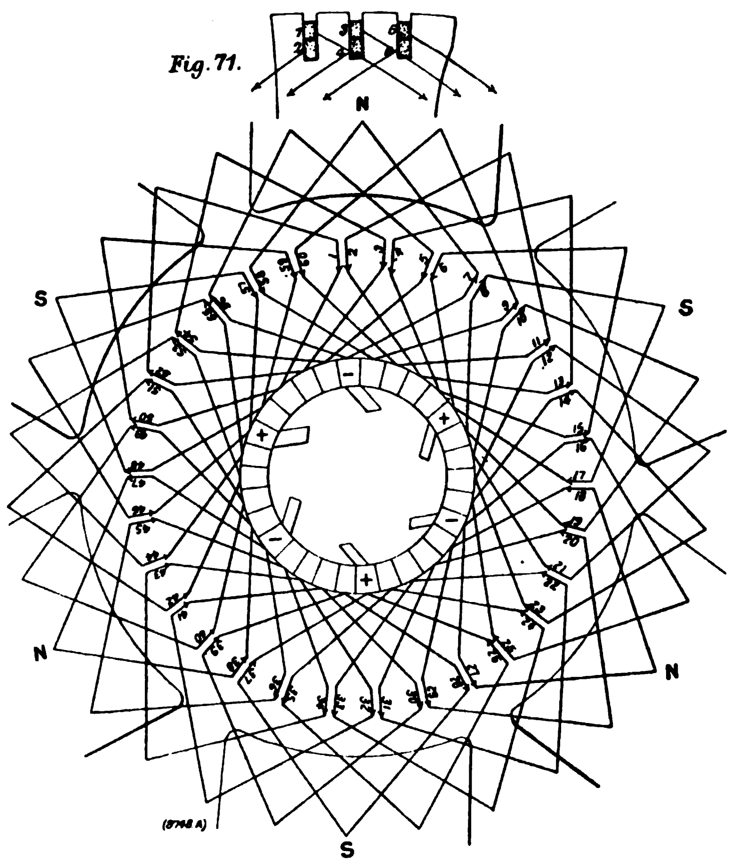


FIG. 71. MULTIPLE-CIRCUIT, DRUM WINDING

double-spiral arrangement or its equivalent, the best mechanical result will be secured by always connecting an upper to a lower conductor; hence the necessity of the pitches being chosen odd.

The small sketch at the top of Fig. 71 shows the actual location of the conductors on the section of the armature. There might, of course, have been only one conductor per slot; or when desirable, there could be more than two. The grouping of the conductors in the diagram in pairs is intended to indicate an arrangement with two conductors

per slot. But in subsequent diagrams it will be more convenient to arrange the face of the conductors equi-distantly.

The following is a summary of the conditions governing multiple-circuit single windings, such as that shown in Fig. 71 :

a. There may be any even number of conductors, except that in iron-clad windings the number of conductors must also be a multiple of the number of slots.

b. The front and back pitches must both be odd, and must differ by 2 ; therefore the average pitch is even.

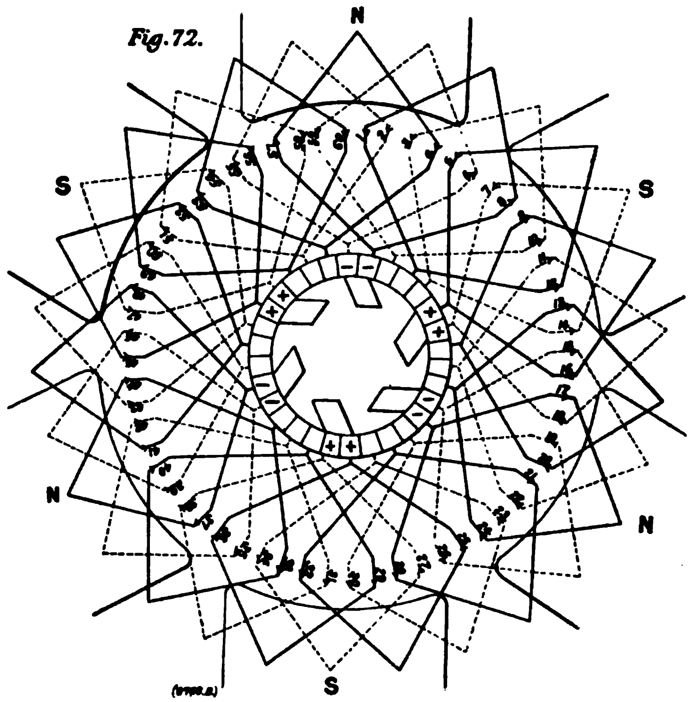


Fig. 72. Six-Circuit, Double-Winding

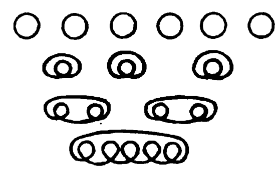
c. The average pitch y should not be very different from c/n when c = number of conductors, and n = number of poles. For chord windings, y should be smaller than c/n by as great an amount as other conditions will permit, or as may be deemed desirable.

Multiple-circuit windings may also be multiple-wound, instead of being single-wound, as in the above instance. We refer to a method in which two or more single windings may be superposed upon the same armature, each furnishing but a part of the total current of the machine. The rules governing such windings are somewhat elaborate, and it is not necessary at present to go fully into the matter. In Fig. 72 is shown a six-circuit

double winding. Each of the two windings is a multiple-circuit winding, with six circuits through the armature, so that the arrangement results in only one-twelfth of the sixty conductors being in series between negative and positive brushes; each of the conductors, consequently, carrying one-twelfth of the total current. This particular winding is of the doubly re-entrant variety. That is to say, if one starts at conductor 1, and traces through the conducting system, conductor 1 will be re-entered when only half of the conductors have been traced through. The other half of the conductors form an entirely separate conducting system, except in so far as they are put into conducting relation by the brushes. If fifty-eight conductors are chosen, instead of sixty, the winding becomes singly re-entrant, *i.e.*, the whole winding has to be traced through before the original conductor is again reached.

A singly re-entrant double winding is symbolically denoted thus ◎, and a doubly re-entrant double winding by O O. There is no limit for such arrangements. Thus we may have

Sextuply re-entrant, sextuple windings,
Triply re-entrant, sextuple windings,
Doubly re-entrant, sextuple windings,
Singly re-entrant, sextuple windings,



by suitable choice of total conductors and pitch. In practice, multiple windings beyond double, or at most triple, would seldom be used. Such windings are applicable to cases where large currents are to be collected at the commutator. Thus, in the case of a triple winding, the brushes should be made of sufficient width to bear at once on at least four segments, and one-third of the current passing from the brush will be collected at each of three points of the bearing surface of the brush, such division of the current tending to facilitate its sparkless collection. A double winding has twice as many commutator segments as the equivalent single winding. Another property is that the bridging of two adjacent commutator segments by copper or carbon dust does not short-circuit any part of the armature winding, and an arc is much less likely to be established on the commutator from any cause.

Two-Circuit Drum Windings

Two-circuit drum windings are distinguished by the fact that the pitch is always forward, instead of being alternately forward and backward, as in the multiple-circuit windings.

The sequence of connections leads the winding from a certain bar opposite one pole-piece to a bar similarly situated opposite the next pole-piece, and so on, so that as many bars as pole-pieces are passed through before another bar in the original field is reached.

A two-circuit single winding in a six-pole field is shown in Fig. 73. Two-circuit windings have but two paths through the armature, independently of the number of poles. Only two sets of brushes are needed, no matter how many poles there may be, so far as collection of the current

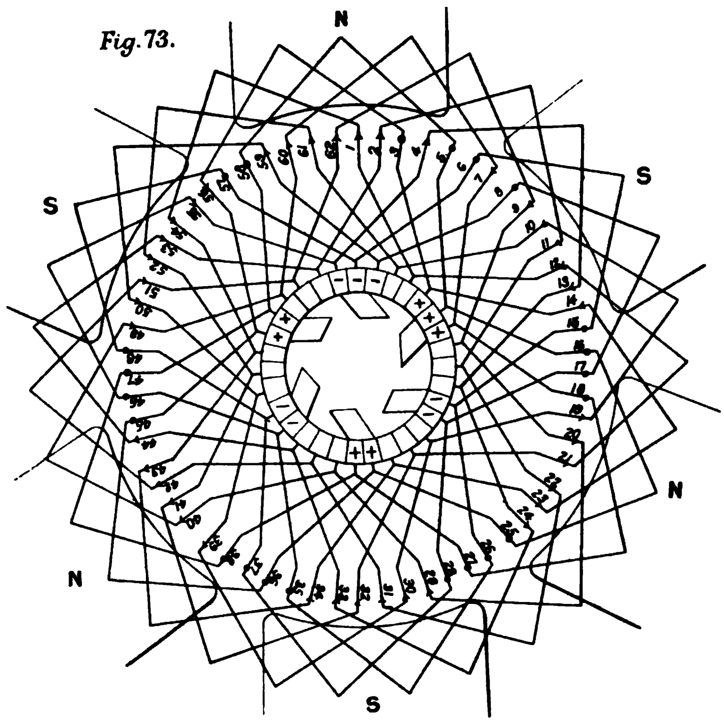


FIG. 73. TWO-CIRCUIT, SINGLE WINDING

is concerned; but in order to prevent the commutator being too expensive, it is customary in large machines to use as many sets of brushes as there are pole-pieces. Where more than two sets of brushes must be used, that is, in machines of large current output, the advantages possible from equal currents in the two circuits have been overbalanced by the increased sparking, due to unequal division of the current between the different sets of brushes of the same sign.

An examination of the diagrams will show that in the two-circuit windings, the drop in the armature, likewise the armature reaction, is independent of any manner in which the current may be subdivided among

the different sets of brushes, but depends only upon the sum of the currents at all the sets of brushes at the same sign. There are in the two-circuit windings no features that tend to cause the current to subdivide equally between the different sets of brushes of the same sign; and in consequence, if there is any difference in contact resistance between the different sets of brushes, or if the brushes are not set with the proper lead with respect to each other, there will be an unequal division of the current.

When there are as many sets of brushes as poles, the density at each pole must be the same; otherwise the position of the different sets of brushes must be shifted with respect to each other to correspond to the different intensities, the same as in the multiple-circuit windings.

In practice it has been found difficult to prevent the shifting of the current from one set of brushes to another. The possible excess of current at any one set of brushes increases with the number of sets; likewise the possibility of excessive sparking. For this reason the statement has been sometimes made that the disadvantages of the two-circuit windings increase in proportion to the number of poles.

From the above it may be concluded that any change of the armature with respect to the poles will, in the case of two-circuit windings, be accompanied by shifting of the current between the different sets of brushes; therefore, to maintain a proper subdivision of the current, the armature must be maintained in one position with respect to the poles, and with exactness, since there is no counter action in the armature to prevent the unequal division of the current.

But in the case of multiple-circuit windings, it will be noted that the drop in any circuit, likewise the armature reaction on the field in which the current is generated, tend to prevent an excessive flow of current from the corresponding set of brushes. On account of these features (together with the consideration that when there are as many brushes as poles the two-circuit armatures require the same nicety of adjustment with respect to the poles as the multiple-circuit windings), the latter are generally preferable, even when the additional cost is taken into consideration.

In the section upon "The Electro-Magnetic Limit of Output," it will be shown that the limitations imposed by the use of practicable electro-magnetic constants restrict the application of two-circuit windings to machines of relatively small output.

Two circuit windings may be multiple as well as single-wound. Thus

in Fig. 74 we have a two-circuit, doubly re-entrant, double winding. An illustration of the convenience of a double winding, in a case where either one of two voltages could be obtained without changing the number of face conductors, may be given by that of a six-pole machine with 104 armature conductors. The winding may be connected as a two-circuit single winding by making the pitch 17 at each end, or as a two-circuit doubly re-entrant double winding, by making the pitch 17 at one end and 19 at the other.

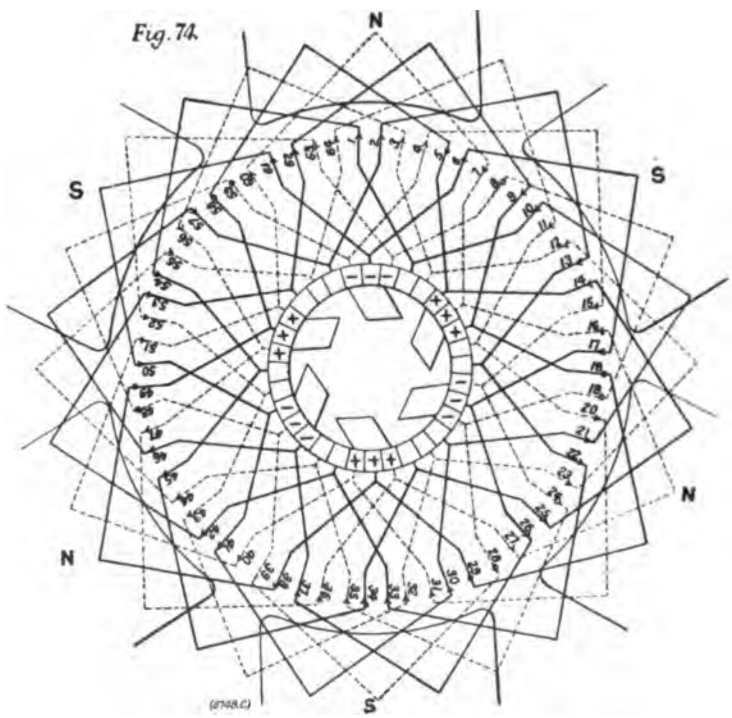


Fig. 74. Two-Circuit, Double Winding

The second would be suitable for the same watt output as the first, but at one-half the voltage and twice the current.

Formula for Two-Circuit Windings

The general formula for two-circuit windings is:

$$C = ny \pm 2m.$$

where

C = number of face conductors.
n = number of poles.
y = average pitch.
m = number of windings.

The m windings will consist of a number of independently re-entrant windings, equal to the greatest common factor of y and m. Therefore, where it is desired that the m windings shall combine to form one re-entrant system, it will be necessary that the greatest common factor of y and m be made equal to 1.

Also, when y is an even integer the pitch must be taken alternately, as $(y-1)$ and $(y+1)$, instead of being taken equal to y.

Thus, in the case of the two-circuit single windings we have

$$C = ny \pm 2$$

and in double windings (m being equal to 2) we have

$$C = ny \pm 4.$$

As a consequence of these and other laws controlling the whole subject of windings, many curious and important relations are found to exist between the number of conductors, poles, slots, pitches, &c., and with regard to re-entrancy and other properties.[1]

Windings for Rotary Converters

As far as relates to their windings, rotary converters consist of continuous-current machines in which, at certain points of the winding, connections are made to collector rings, alternating currents being received or delivered at these points.

The number of sections into which such windings should be subdivided are given in the following Table:

Table XVIII.

	Two-Circuit Single Winding. Sections.	Multi.-Circuit Single Winding. Sections per Pair Poles.
Single-phase rotary converter	2	2
Three-phase rotary converter	3	3
Quarter-phase rotary converter	4	4
Six-phase rotary converter	6	6

For *multiple* windings, the above figures apply to the number of

[1] $y - 3$ and $y + 3$, etc., also give re-entrant systems, but the great difference between the pitches at the two ends would make their use very undesirable except in special cases; thus, for instance, it would be permissible with a very large number of conductors per pole.

sections per winding: thus, a three-phase converter with a two-circuit double winding would have $3 \times 2 = 6$ sections per pair of poles. In the case of the three-phase rotary converter winding shown in Fig. 75, which is a two-circuit single winding, connection should be made from a conductor to one of the collector rings, and the winding should be traced through until one-third of the total face conductors have been traversed. From this point, connection should be made to another collector ring. Tracing through another third, leads to the point from which connection

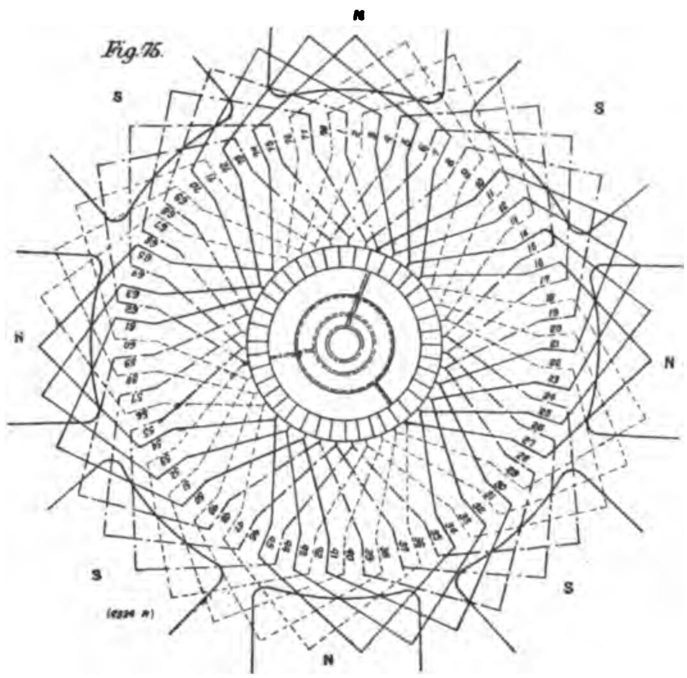


FIG. 75. THREE-PHASE ROTARY CONVERTER, TWO-CIRCUIT SINGLE WINDING

should be made to the remaining collector ring, between which and the first collector ring the remaining third of the total number of conductors would be found to lie. It is desirable to select a number of conductors, half of which is a multiple of three, thus giving an equal number of pairs of conductors in each branch. Where a multiple-circuit winding is used, the number of conductors per pair of poles should be twice a multiple of three. A multiple-circuit three-phase rotary converter winding is given in Fig. 76. Further information regarding the properties of rotary converters, and the resultant distribution of current in their windings, is reserved for the section on "Rotary Converters."

Alternating Current Windings

In general, any of the continuous-current armature windings may be employed for alternating current work, but the special considerations leading to the use of alternating currents generally make it necessary to abandon the styles of winding best suited to continuous-current work, and to use windings specially adapted to the conditions of alternating current practice.

Attention should be called to the fact that all the re-entrant (or closed circuit) continuous-current windings must necessarily be two-circuit or

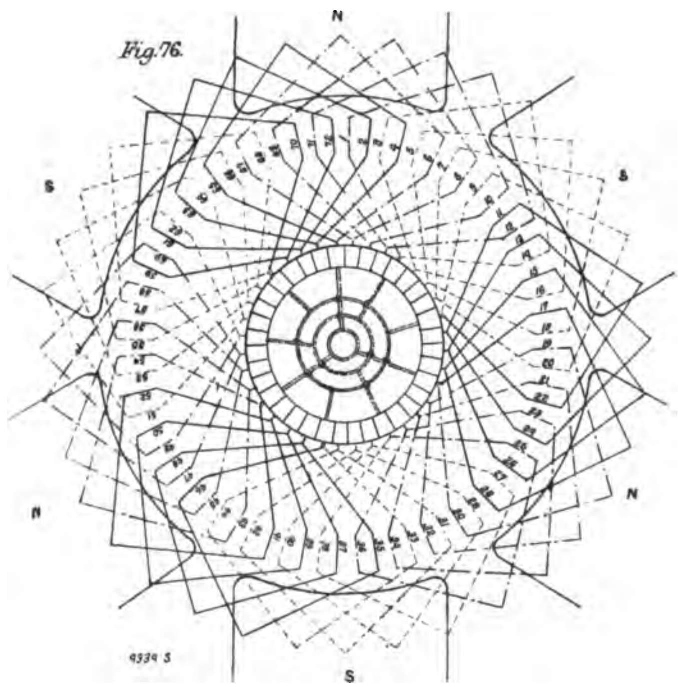


Fig. 76. Three-Phase Rotary Converter, Six-Circuit Winding

multiple-circuit windings, while alternating current armatures may, and generally do, from practical considerations, have one-circuit windings, *i.e.*, one circuit per phase. From this it follows that any continuous-current winding may be used for alternating current work, but an alternating current winding cannot generally be used for continuous-current work. In other words, the windings of alternating current armatures are essentially non-re-entrant (or open circuit) windings, with the exception of the ring-connected polyphase windings, which are re-entrant (or closed circuit) windings. These latter are, therefore, the only windings which are applicable to alternating-continuous-current commutating machines.

Usually for single-phase alternators, one slot or coil per pole-piece is used (as shown in Figs. 77 and 78, page 78), and this permits of the most effective disposition of the armature conductors as regards generation of electromotive force. If more slots or coils are used (as in Fig. 79), or, in the case of face windings,[1] if the conductors are more evenly distributed over the face of the armature, the electromotive forces generated in the various conductors are in different phases, and the total electromotive force is less than the algebraic sum of the effective electromotive forces induced in each conductor.

But, on the other hand, the subdivision of the conductors in several slots or angular positions per pole, or, in the case of face windings, their more uniform distribution over the peripheral surface, decreases the inductance of the winding, with its attendant disadvantages. It also utilises more completely the available space, and tends to bring about a better distribution of the necessary heating of core and conductors. Therefore, in cases where the voltage and the corresponding necessary insulation permit, the conductors are sometimes spread out to a greater or less extent from the elementary groups necessary in cases where very high potentials are used. Windings in which such a subdivision is adopted are said to have a multi-coil construction (Fig. 79), as distinguished from the form in which the conductors are assembled in one group per pole-piece (Figs. 77 and 78), which latter are called unicoil windings.

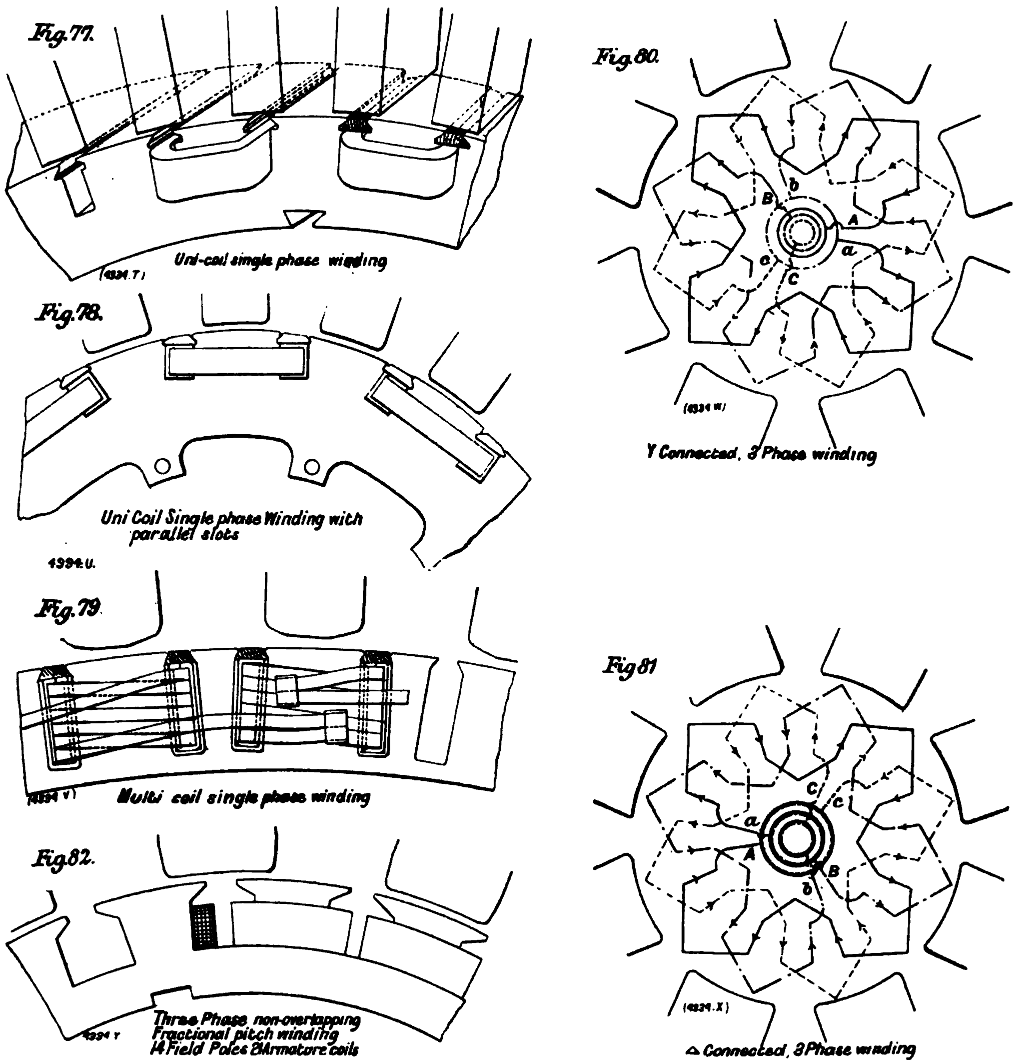
In most multiphase windings, multi-coil construction involves only very slight sacrifice of electromotive force for a given total length of armature conductor, and in good designs is generally adopted to as great an extent as proper space allowance for insulation will permit.

It is desirable to emphasise the following points regarding the relative merits of unicoil and multi-coil construction. With a given number of conductors arranged in a multi-coil winding, the electromotive force at the terminals will be less at no load than would be the case if they had been arranged in a unicoil winding; and the discrepancy will be greater in proportion to the number of coils into which the conductors per pole-piece are subdivided, assuming that the spacing of the groups of conductors is uniform over the entire periphery.

But when the machine is loaded, the current in the armature causes reactions which play an important part in determining—as will be shown

[1] Otherwise often designated "smooth core windings," as opposed to "slot windings."

later—the voltage at the generator terminals; and this may only be maintained constant as the load comes on, by increasing the field excitation, often by a very considerable amount. Now, with a given number of armature conductors, carrying a given current, these reactions are greatest when the armature conductors are concentrated in one group per pole-piece



FIGS. 77 TO 82. DIFFERENT TYPES OF WINDING

(Figs. 77 and 78); that is, when the unicoil construction is adopted; and they decrease to a certain degree in proportion as the conductors are subdivided into small groups distributed over the entire armature surface, that is, they decrease when the multi-coil construction (Fig. 79) is used. Consequently, there may be little or no gain in voltage *at full load* by the

use of a unicoil winding over that which would have been obtained with a multi-coil winding of an equal number total of turns, although at *no load* the difference would be considerable. This matter will be found treated from another standpoint in the section on "Formulæ for Electromotive Force."

Multi-coil design (Fig. 79) also results in a much more equable distribution of the conductors; and, in the case of iron-clad construction, permits of coils of small depth and width, which cannot fail to be much more readily maintained at a low temperature for a given cross-section of conductor; or, if desirable to take advantage of this point in another way, it should be practicable to use a somewhat smaller cross-section of conductor for a given temperature limit. A final advantage of multi-coil construction is that it results in a more uniform reluctance of the magnetic circuit for all positions of the armature; as a consequence of which, hysteresis and eddy current losses are more readily avoided in such designs. A thorough discussion of this matter is given in the section relating to the design of the magnetic circuit.

The unicoil winding of Fig. 77 may often with great advantage be modified in the way shown in Fig. 78, where the sides of the tooth are parallel, enabling the form-wound coil to be readily slipped into place. The sides of the slots are notched for the reception of wedges, which serve to retain the coil in place. Parallel-sided slots become more essential the less the number of poles. For very large numbers of poles, radial slots are practically as good.

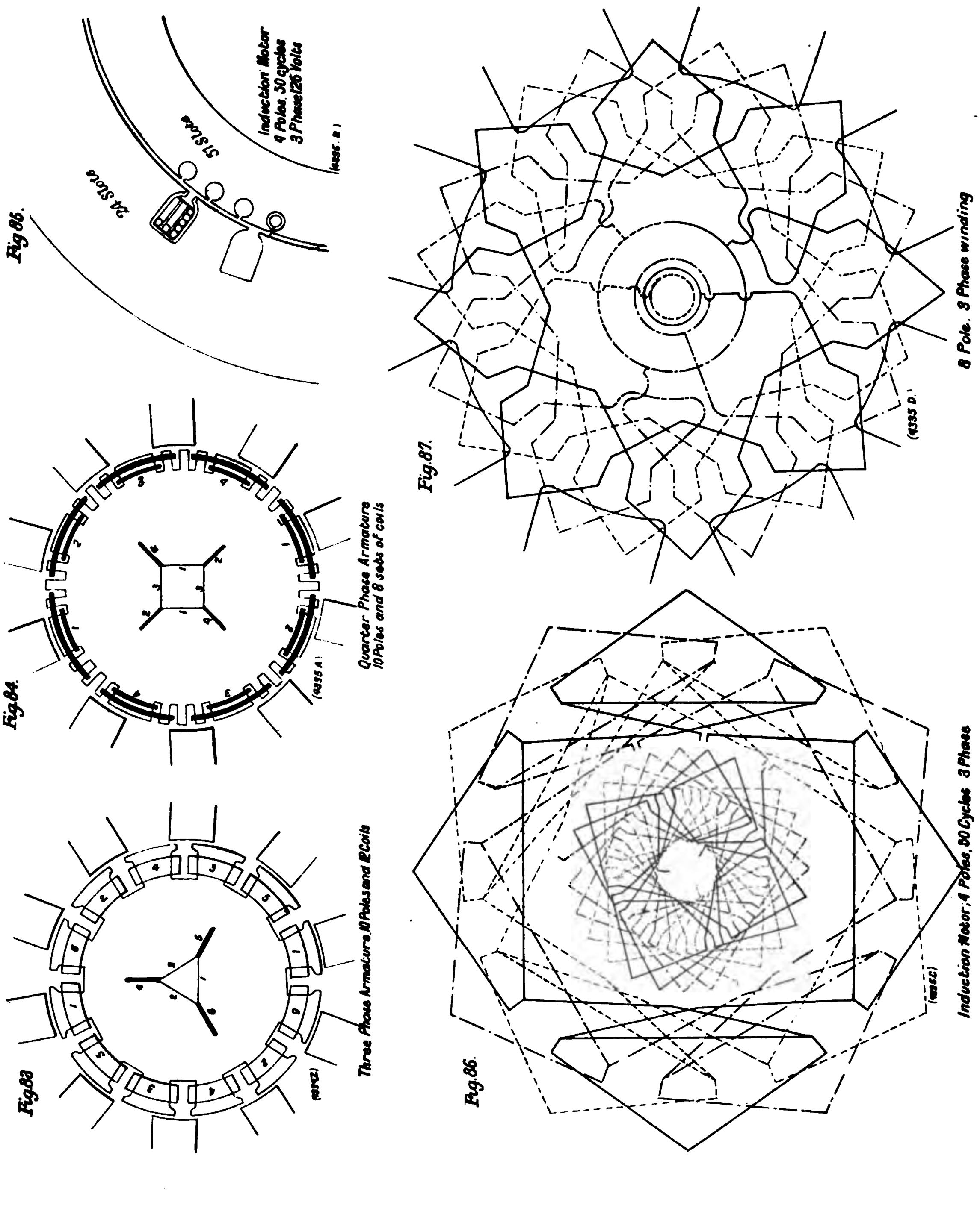
Fig. 80 shows a **Y**-connected unicoil three-phase winding; Fig. 81 differs from it only in having the windings of the three-phases Δ connected.

Fig. 82 gives a portion of a three-phase winding, with fourteen field poles and twenty-one armature coils (three coils per two-pole pieces). This is a representative of a type of windings known as fractional pitch windings, the relative merits of which will be discussed in the section on the design of polyphase generators. The diagrams in Figs. 83 and 84, page 80, give two more examples of fractional pitch—polyphase windings.[1]

Induction Motor Windings

The windings of induction motors are not essentially different from many already described. In order to keep the inductance low, the

[1] See also British Patent Specification No. 30,264, 1897.



FIGS. 83 TO 87. DIFFERENT TYPES OF WINDING

windings both for the rotor and stator are generally distributed in as many coils as there can be found room for on the surface, instead of being concentrated in a few large coils of many turns each. This becomes of especial importance in motors of large capacity; in smaller motors the windings may consist of comparatively few coils. This is the case in Fig. 85, where the stator winding of a 7½ horse-power four-pole three-phase motor is divided up into two slots per pole-piece per phase. The rotor, whose winding is generally made up of few conductors, each of large cross-section, is often most conveniently arranged with but one conductor per slot, as shown in Fig. 85. The connection diagrams of these stator and rotor windings are given in Fig. 86. Fig. 87 gives a useful type of winding for either the stator or the rotor of induction motors, the conductors, represented by radial lines, being, in the case of the stator, generally replaced by coils.

FORMULÆ FOR ELECTROMOTIVE FORCE

In this section, the dynamo will be considered with reference to the electromotive force to be generated in the armature.

Continuous-Current Dynamos

The most convenient formula for obtaining the voltage of continuous-current dynamos is:

$$V = 4.00\ T N M\ 10^{-8}.$$

in which

V = the voltage generated in the armature.
T = the number of turns in series between the brushes.
N = the number of magnetic cycles per second.
M = the magnetic flux (number of C G S lines) included or excluded by each of the T turns in a magnetic cycle.

V, the voltage, is approximately constant during any period considered, and is the integral of all the voltages successively set up in the different armature coils according to their position in the magnetic field; and since in this case only average vòltages are considered, the resultant voltage is independent of any manner in which the magnetic flux may vary through the coils. Therefore we may say that for continuous-current dynamos, the voltage is unaffected by the shape of the magnetic curve, *i.e.*, by the distribution of the magnetic flux.

It will be found that the relative magnitudes of T, N, and M may (for a given voltage) vary within wide limits, their individual magnitudes being controlled by considerations of heating, electro-magnetic reactions, and specific cost and weight.

This formula, if correctly interpreted, is applicable whether the armature be a ring, a drum, or a disc; likewise for two-circuit and multiple-circuit windings, and whether the winding be single, double, triple, &c.

To insure, in all cases, a correct interpretation of the formula, it will be desirable to consider these terms more in detail :

T = turns in series between brushes,

i.e., total turns on armature divided by number of paths through armature from negative to positive brushes.

For a Gramme-ring armature, total turns = number of face conductors.

For a drum armature, total turns = $\frac{1}{2}$ number of face conductors.

With a given number of total turns, the turns in series between brushes depend upon the style of winding, thus :

For two-circuit winding,

If single, two paths, independently of the number of poles.
If double, four paths, independently of the number of poles.
If triple, six paths, independently of the number of poles, &c.

For multiple-circuit winding,

If single, as many paths as poles.
If double, twice as many paths as poles.
If triple, three times as many paths as poles, &c.

$$N = \text{the number of magnetic cycles per second}$$
$$= \frac{\text{R.P.M.} \times \text{number of pairs of poles}}{60}.$$

It has been customary to confine the use of this term (cycles per second) to alternating current work, but it is desirable to use it also with continuous currents, because much depends upon it. Thus N, the periodicity, determines or limits the core loss and density, tooth density, eddy current loss, and the armature inductance, and, therefore also affects the sparking at the commutator. It is, of course, also necessarily a leading consideration in the design of rotary converters.

Although in practice dynamo speeds are expressed in revolutions per minute, the periodicity N is generally expressed in cycles per second.

M = flux linked successively with each of the T turns.

In the case of the

Gramme-ring machine, $M = \frac{1}{2}$ flux from one pole-piece into armature.
Drum machine, M = total flux from one pole-piece into armature.

(M is not the flux *generated* in one pole-piece, but that which, after deducting leakage, finally not only crosses the air-gap, but passes to the roots of the teeth, thus linking itself with the armature turns.)

Armature cores are very often built up as rings for the sake of ventilation, and to avoid the use of unnecessary material; but they may be, and usually are, wound as drums, and should not be confounded with Gramme-wound rings.

The accompanying Table of drum-winding constants affords a convenient means of applying the rules relating to drum windings.

TABLE XIX.—DRUM-WINDING CONSTANTS

—	Class of Winding.		Number of Poles. 4.	6.	8.	10.	12.	14.	16.
Volts per 100 conductors per 100 revolutions per minute and flux equal to one megaline	Multiple-circuit	Single	1.667	1.667	1.667	1.667	1.667	1.667	1.667
		Double	.833	.833	.833	833	.833	.833	.833
		Triple	.556	.556	.556	.556	.556	.556	.556
	Two-circuit	Single	3.33	5.00	6.67	8.33	10.00	11.67	13.33
		Double	1.667	2.50	3.33	4.17	5.00	5.83	6.67
		Triple	1.111	1.667	2.22	2.78	3.33	3.89	4.44
Average volts between commutator segments, per megaline and per 100 revolutions per minute (independent of number of conductors)	Multiple-circuit	Single	.1333	.200	.267	.333	.400	.467	.533
		Double	.0668	.100	.1333	.1667	.200	.233	.267
		Triple	.0445	.0667	.0888	.1111	.1333	.1555	.1778
	Two-circuit	Single	.267	.600	1.068	1.668	2.40	3.27	4.27
		Double	.1333	.300	.534	.834	1.200	1.635	2.14
		Triple	.0888	.200	.356	.556	.800	1.09	1.42

ALTERNATING CURRENT DYNAMOS

For alternating current dynamos it is often convenient to assume that the curve of electromotive force is a sine wave. This is frequently not the case; and, as will presently be seen, it is practicable and often necessary to consider the actual conditions of practice instead of assuming the wave of electromotive force to be a sine curve.

CURVE OF ELECTROMOTIVE FORCE ASSUMED TO BE A SINE WAVE

The formula for the effective no-load voltage at the collector ring is:

$$V = 4.44\, T\, N\, M\, 10^{-8}.$$

this being the square root of the mean square value of the sine wave of electromotive force whose maximum value is:

$$V = 6.28\, T\, N\, M\, 10^{-8}.$$

In order that these formulæ may be used, the electromotive force wave must be a sine curve, *i.e.*, the magnetic flux must be so distributed as to

give this result. The manner of distribution of the magnetic flux in the gap, necessary to attain this result, is a function of the distribution of the winding over the armature surface.

T = number of turns in series between brushes.
N = number of magnetic cycles per second.
M = number of C G S lines *simultaneously* linked with the T turns.

The flux will be *simultaneously* linked with the T turns only in the case of unicoil windings, *i.e.*, windings in which the conductors are so grouped that they are all similarly situated in respect to the magnetic flux; in other words, they are all in the same phase.[1]

The effective voltage at no load, generated by a given number of turns, will be a maximum when that is the case; and if the voltage for such a case be represented by unity, then the same number of conductors arranged in "two-coil," "three-coil," &c., windings will, with the same values for T, N, M, generate (at no load) voltages of the relative values, .707, .667, &c.; until, when we come to a winding in which the conductors are distributed over the entire surface, as in ordinary continuous-current dynamos, the relative value of the alternating current voltage at no load, as compared with that of the same number of turns arranged in a unicoil winding, will be .637 $\left(\text{which} = \frac{2}{\pi}\right)$.

Tabulating these results we have:

TABLE XX

	Correction Factor for Voltage of Distributed Winding.
Unicoil winding	... V = 1.000
Two-coil winding	... V = .707 × unicoil winding.
Three-coil winding	... V = .667 × " "
Four-coil winding	... V = .654 × " "
Many-coil winding	... V = .637 × " "

The terms uni-, two-, three-coil, &c., in the above Table indicate whether the conductors are arranged in one, two, three, &c., equally-spaced groups per pole-piece. The conditions are equivalent to the component electromotive forces generated in each group; being in one, two, three, &c., different phases, irrespective of the number of resultant windings into which they are combined.

[1] Fig. 88, on page 88 will be of assistance in understanding the nomenclature employed in designating these windings.

The values given in the Table may be easily deduced by simple vector diagrams.

Instead of using such "correction factors," the following values may be substituted for K in the formula $V = K T N M 10^{-8}$:

TABLE XXI

—	Values for K in Formula.	
	For Effective Voltage.	For Maximum Voltage.
Unicoil winding	4.44	6.28
Two-coil "	3.13	4.44
Three-coil "	2.96	4.19
Four-coil "	2.90	4.11
Many-coil "	2.83	4.00

(In all the preceding cases, as they apply only to sine wave curves, the maximum value will be 1.414 times the effective value.)

VALUES OF K FOR VARIOUS WAVES OF ELECTROMOTIVE FORCE AND OF MAGNETIC FLUX DISTRIBUTION IN GAP

The relative width and arrangement of pole arc and armature coil exert a great influence upon the magnitude of the effective (and maximum) voltage for given values of T, N, M, because of the different shapes of the waves of gap distribution and induced electromotive force. This is shown by Tables XXII. and XXIII., where are given the values of K in the formula:

$$V = K T N M 10^{-8},$$

it being assumed that the magnetic flux M emanates uniformly from the pole face, and traverses the gap along lines normal to the pole face. This assumption being usually far from the facts, the following results must be considered more in the light of exhibiting the *tendency* of various relative widths of pole face and the various arrangements of armature coil, rather than as giving the actual results which would be observed in practice. The results are, nevertheless, of much practical value, provided it is clearly kept in mind that they will be modified to the extent by which the flux spreads out in crossing the gap from pole face to armature face.

The following Table applies to cases where the various components of the total winding are distributed equi-distantly over the armature.

TABLE XXII.—VALUES FOR K
In the Formula V = K T N M 10^{-8}, where V = Effective Voltage

Winding.	Pole Arc (expressed in per Cent. of Pitch).									
	10.	20.	30.	40.	50.	60.	70.	80.	90.	100.
Unicoil	12.6	8.96	7.30	6.32	5.66	5.17	4.78	4.46	4.21	4.00
Two-coil	8.96	6.32	5.17	4.46	4.00	3.64	3.40	3.12	3.00	2.83
Three-coil	7.30	5.17	4.21	3.84	3.55	3.35	3.08	2.90	2.76	2.55
Four-coil	6.32	4.46	4.00	3.72	3.45	3.24	3.02	2.83	2.63	2.45
Many-coil	3.93	3.79	3.63	3.44	3.27	3.08	2.88	2.70	2.52	2.32

When the coils are gathered in groups of a greater or less width, the values of K should be taken from Table XXIII. given below.

A better understanding of the nomenclature employed in these two Tables will be obtained by an examination of the diagrams in Fig. 88.

Probably the method used in obtaining these values (simple graphical plotting) is substantially that used by Kapp in 1889. The six values he gives check the corresponding ones in Tables XXII and XXIII.

TABLE XXIII.—VALUES OF K
In the Formula V = K T N M 10^{-8}, where V = Effective Voltage

Spread of Armature Coil in per Cent. of Pitch.	Pole Arc (expressed in per Cent. of Pitch).									
	10.	20.	30.	40.	50.	60.	70.	80.	90.	100.
0	12.60	8.96	7.30	6.32	5.66	5.17	4.78	4.46	4.21	4.00
10	9.80	8.20	6.85	6.00	5.50	5.05	4.74	4.42	4.15	3.88
20	8.20	7.40	6.55	5.75	5.25	4.90	4.60	4.35	4.05	3.75
30	7.10	6.55	6.00	5.45	5.05	4.75	4.45	4.20	3.90	3.60
40	6.20	5.80	5.45	5.15	4.85	4.55	4.30	4.00	3.72	3.43
50	5.60	5.32	5.10	4.85	4.60	4.35	4.10	3.85	3.60	3.27
60	5.08	4.90	4.71	4.55	4.39	4.15	3.95	3.68	3.40	3.10
70	4.72	4.60	4.44	4.30	4.18	3.95	3.75	3.45	3.20	2.90
80	4.44	4.30	4.15	4.00	3.85	3.66	3.50	3.25	3.00	2.75
90	4.18	4.00	3.90	3.75	3.60	3.40	3.20	3.00	2.78	2.55
100	3.93	3.79	3.63	3.44	3.27	3.08	2.88	2.70	2.52	2.32

It thus appears that by merely varying the spread of the pole arc and the armature coil, there may be obtained for given values of T, N, and M, values of the effective electromotive force, varying from a little more than half the corresponding value for a sine wave, up to several times that value (in fact, with an infinitely small spread of pole arc, provided the flux could be maintained, an infinitely large value of K would be obtained). The maximum value increases at the same time, in a still greater proportion.

ROTARY CONVERTERS

In rotary converters we have an ordinary distributed continuous-current-winding, supplying continuous-current voltage at the commutator, and alternating-current voltage at the collector-rings. The same winding, therefore, serves both for continuous-current voltage and for alternating voltage.

Suppose that such a distributed winding, with given values of T, N, and M, generates a continuous-current voltage V at the commutator. Imagine superposed on the same armature a winding, with the same number of turns T in series, but with these turns concentrated in a unicoil winding. For the same speed and flux, and assuming a sine wave curve of

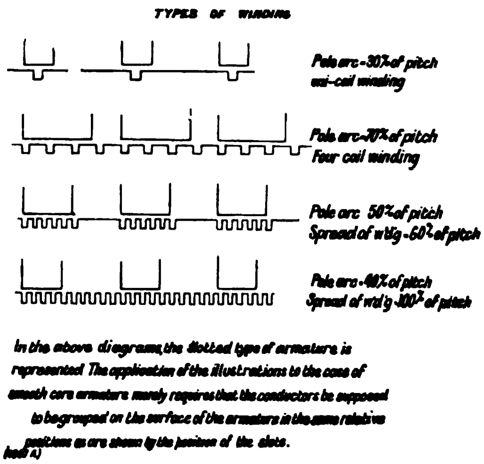


FIG. 88. DIFFERENT TYPES OF WINDING

electromotive force, this imaginary superposed winding would supply 1.11 V, $\left(= \frac{\pi}{2\sqrt{2}} V\right)$ effective volts to the collector rings. But, re-arranging this same number of turns in a "many-coil" (distributed) winding, would, for the same speed and flux, reduce the collector ring voltage to

$$.637 \times 1.11 \times V = .707 \times V$$

Therefore, in a distributed winding, with T turns in series, there will be obtained a continuous-current voltage V, and an alternating-current voltage .707 V, on the assumption of a sine wave curve of electromotive force.

But often the electromotive force curve is not a sine wave, and the value of the voltage becomes a function of the pole arc. Thus, examining the case of a single or quarter-phase rotary converter by the aid of the Tables for K, the results given in Table XXIV. are obtained.

TABLE XXIV.—SINGLE AND QUARTER-PHASE ROTARY CONVERTERS

Spread of Pole Arc in per Cent. of Pitch.	K in $V = K\,T\,N\,M\,10^{-8}$ for Collector Ring Voltage.	K for Continuous-Current Voltage.	Ratio of Alternating Voltage between Collector-Rings to Continuous-Current Voltage at Commutator.
10	3.93	4.00	.982
20	3.79	4.00	.947
30	3.63	4.00	.908
40	3.44	4.00	.860
50	3.27	4.00	.816
60	3.08	4.00	.770
70	2·88	4.00	.720
80	2.70	4.00	.675
90	2.52	4.00	.630
100	2.32	4.00	.580

THREE-PHASE ROTARY CONVERTERS

An examination of three-phase rotary converters will show that the conductors belonging to the three phases have relative positions on the armature periphery, which may be represented thus:

2222211111111111333333333332222222222211111111113333333333322222
3333333333322222222222111111111133333333333222222222221111111111

Consequently, it appears that the coils of one phase have a spread equal to 66.7 per cent. of the pitch. Observing also that each three-phase alternating branch has two-thirds as many turns in series between collector rings as has each branch, considered with reference to the commutator brushes, we obtain the following Table of values:

TABLE XXV.—THREE-PHASE ROTARY CONVERTERS

Spread of Pole Arc in per Cent. of Pitch.	K in $V = K\,T\,N\,M\,10^{-8}$ for Collector-Ring Voltage.	K for Continuous-Current Voltage.	Ratio of Alternating Voltage between Collector-Rings to Continuous-Current Voltage at Commutator.
10	4.89	4.00	.815
20	4.70	4.00	.785
30	4.53	4.00	.755
40	4.39	4.00	.732
50	4.25	4.00	.710
60	4.02	4.00	.670
70	3.82	4.00	.636
80	3.52	4.00	.585
90	3.26	4.00	.544
100	2.96	4.00	.495

The last column, giving the ratio of alternating-current voltage between collector rings, to continuous-current voltage at commutator, is the one of chief interest. This ratio varies from .495, when the pole arc is equal to the pitch, up to .815 with a 10 per cent. pole arc.

These results only apply to rotary converters when independently driven, unloaded, from some mechanical source, or when driven unloaded as a continuous-current motor. That is to say, the electromotive forces referred to are counter-electromotive forces. When driven synchronously, the ratio of the terminal voltages may be made to vary through a very wide range by varying the conditions of lag and lead of the current in

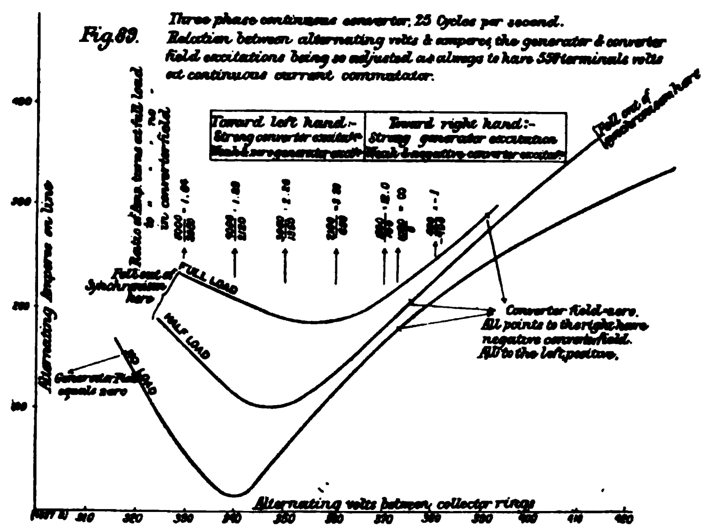


FIG. 89. ROTARY CONVERTER CHARACTERISTIC CURVE

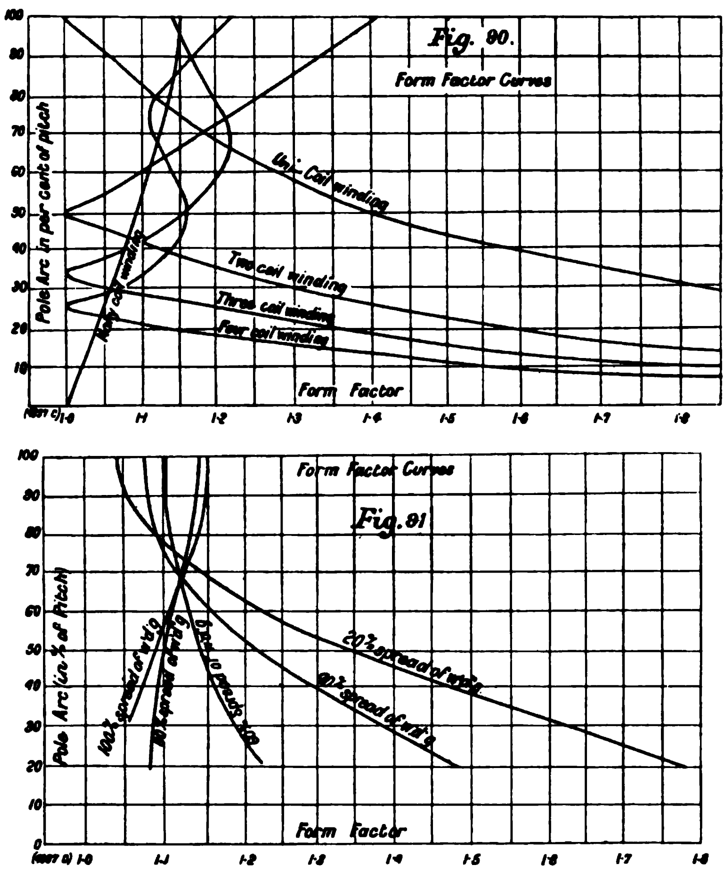
the armature. In Fig. 89 is given a curve showing through what a very extended range this ratio may be varied, according to the conditions of load and excitation.

TABLE XXVI

Converter.	Proportion that T is of Turns on Arm.	
	2-Circuit Winding.	Multiple-Circuit Winding.
Single-phase rotary	$\frac{1}{2}$	$\frac{1}{2 \times \text{number of pairs of poles}}$
Quarter-phase rotary... ...	$\frac{1}{2}$	$\frac{1}{2 \times \text{number of pairs of poles}}$
Three-phase rotary	$\frac{1}{3}$	$\frac{1}{3 \times \text{number of pairs of poles}}$

In rotary converters, Table XXVI. will be of assistance in determining the value of T (number of turns in series between collector rings).

Polyphase Machines.—In considering polyphase machines in general, it may be said that the most convenient way of considering the relations between V, T, N, and M, is to make the calculations for one phase. Thus in the case of a three-phase machine, one would calculate the volts per



FIGS. 90 AND 91. FORM FACTOR CURVES

phase, by using as T, in the formula, the turns in series per phase. Then if the winding is "delta" connected, this will give also the volts between collector rings (since there is only the winding of one phase lying between each pair of collector rings). If, on the other hand, the winding is Y connected, the volts between collector rings will be $\sqrt{3}$, (1.732) times the volts per phase. Thus the calculation should be carried out with reference to one phase, the results of interconnecting the windings of the different phases being subsequently considered.

Electromotive Force and Flux in Transformers

In the case of transformers, the relation between voltage and flux is dependent upon the wave form of the applied electromotive force, and determinations of these quantities involve the use of the term "form factor," proposed by Fleming.[1] He defines the form factor as the ratio of the square root of the mean of the squares of the equi-spaced ordinates of a curve, to the true mean value of the equi-spaced ordinates. The mean square value he denotes by the letters R.M.S. (root mean square), and the mean value by the letters T.M. (true mean).

$$\text{Form factor} = \frac{\text{R.M.S.}}{\text{T.M.}} = f$$

In the case of a rectangular wave, the R.M.S. value, the T.M. value and the maximum value are equal, and the form factor becomes equal to 1. In this case the form factor has the minimum value.

Peaked waves have high form factors. Denoting the form factor by f, the relation between voltage, turns, periodicity, and flux may be expressed by the equation

$$V = 4.00 f \, T \, N \, M \, 10^{-8}.$$

The extent of the dependence of the form factor upon the proportions and winding of the generator may be obtained from Tables XXVII. and XXVIII.; the former applies to equi-distantly distributed windings, and the latter to windings in which the face conductors are gathered in groups more or less spread over the surface of the armature, these groups alternating with unwound spaces.

Table XXVII.—Values for Form Factor (f)

Winding.	Pole Arc (Expressed in Per Cent. of Pitch).									
	10	20	30	40	50	60	70	80	90	100
Uni-coil... ...	3.16	2.24	1.82	1.58	1.41	1.29	1.19	1.12	1.06	1.00
Two-coil... ...	2.24	1.58	1.29	1.12	1.00	1.10	1.18	1.26	1.34	1.41
Three-coil ...	1.82	1.29	1.06	1.08	1.15	1.21	1.22	1.19	1.17	1.15
Four-coil ...	1.58	1.12	1.07	1.13	1.16	1.14	1.11	1.12	1.17	1.22
Many-coil ...	1.02	1.04	1.06	1.08	1.09	1.11	1.12	1.14	1.15	1.15

[1] *Alternate Current Transformers*, vol. i., second edition, page 583.

TABLE XXVIII.—VALUES FOR FORM FACTOR (f)

Spread of Armature Coil in per Cent. of Pitch.	Pole Arc (Expressed in Per Cent. of Pitch.)									
	10	20	30	40	50	60	70	80	90	100
0	3.16	2.24	1.82	1.58	1.41	1.29	1.19	1.12	1.06	1.00
10	2.61	2.05	1.73	1.53	1.37	1.26	1.17	1.11	1.05	1.02
20	2.05	1.83	1.59	1.48	1.31	1.23	1.13	1.08	1.04	1.04
30	1.73	1.59	1.50	1.40	1.25	1.19	1.12	1.07	1.06	1.06
40	1.53	1.48	1.40	1.30	1.21	1.16	1.12	1.09	1.08	1.08
50	1.37	1.31	1.25	1.21	1.17	1.13	1.12	1.09	1.09	1.09
60	1.26	1.23	1.19	1.16	1.13	1.13	1.12	1.11	1.11	1.11
70	1.17	1.13	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
80	1.11	1.08	1.07	1.09	1.09	1.11	1.12	1.13	1.14	1.14
90	1.05	1.04	1.06	1.08	1.09	1.11	1.12	1.14	1.15	1.15
100	1.02	1.04	1.06	1.08	1.09	1.11	1.12	1.14	1.15	1.15

From the formula $V = 4.00 f T N M 10^{-8}$, it appears that for a given effective voltage V, the flux M may be low in proportion as the form factor f is high. This is a distinct advantage in the case of transformers, since their core loss is dependent upon the density of the flux circulating in their iron cores. If a given voltage can be obtained with a small flux, the transformer can be operated at a higher all-day efficiency. Commercial generators of different types differ often by 25 per cent. and more, as regards the form factor of their electromotive force waves. The predetermination of the form factor thus becomes a matter of considerable interest in the design of alternating current generators.

While, however, peaked waves insure low core losses for transformers on the circuits, they have the disadvantage that the maximum electromotive force is more in excess of the effective electromotive force than for the less peaked waves. It is, therefore, generally undesirable to so proportion a generator as to obtain an excessively peaked wave.

The curves of Figs. 90 and 91, page 91, correspond to values given in the Tables, and show the extent of the variations obtainable.

THERMAL LIMIT OF OUTPUT

Viewed from a thermal standpoint, the maximum output of an electric machine is determined by the maximum increase of temperature consistent with good working. The limiting increase of temperature may be determined with respect to durability of the insulating materials used, the efficiency, and the regulation. The increase of temperature is commonly expressed by the ratio of the heat generated in watts, to the radiating surface in square inches, *i.e.*, watts per square inch radiating surface. The increase of temperature of any surface above the atmosphere, and therefore, also, the permissible expenditure of energy per square inch radiating surface, varies according to the nature of the surface, its speed, location, &c. For static surfaces, such as the surfaces of field magnets, the increase of temperature may be taken to be about 80 deg. Cent. per watt per square inch, as measured by a thermometer placed against the cylindrical surface. For cylindrical surfaces of the same nature, but rotated with a peripheral speed of about 3,000 ft. per minute, the increase of temperature per watt per square inch may be taken to be between 30 deg. Cent. and 40 deg. Cent. The increase of temperature per watt per square inch increases as the surface speed is diminished. Thus for smooth-core armatures the increase of temperature is about 25 per cent. greater at a peripheral velocity of 2,000 ft. than at a peripheral velocity of 3,000 ft. per minute. For ventilated armatures of ordinary design, *i.e.*, armatures with interstices, the increase of temperature is between 15 deg. Cent. and 20 deg. Cent. per watt per square inch for a peripheral speed of 3,000 ft. per minute, and between 10 deg. Cent. and 12 deg. Cent. for a peripheral speed of 6,500 ft. per minute.[1] The increase of temperature per watt per square inch varies somewhat with the temperature of the surface, but remains fairly constant for the temperatures used in practice.

In transformers submerged in oil in iron cases, the rise in temperature, as measured by the increased resistance of the windings, is about 35 deg. Cent. per $\frac{1}{10}$ watt per square inch of radiating surface of

[1] The increase of temperature, as determined from resistance measurements, will generally be from 50 per cent. to 100 per cent. in excess of these values. This is clearly shown in the various tests described in the following pages.

the iron case, at the end of ten hours' run. Before this time has elapsed, small transformers will already have reached their maximum temperature, but transformers of 25 kilowatts capacity and larger may continue increasing in temperature for a much longer period. However, transformers are seldom called upon to carry their full load for a longer period than 10 hours. The same transformers, without oil, will have 30 per cent. greater rise.

Large transformers are generally artificially cooled by forced circulation of oil, air, or water, the latter being circulated in pipes coiled about the transformers; and sometimes in the low potential coils of very large transformers the conductors are made tubular, the cooling medium being forced through them. With artificially-cooled transformers, by using sufficient power for forcing the circulation, the rise of temperature may be kept down to almost any value desired. But, of course, the power applied to this purpose lowers the efficiency of the equipment.

Although constants such as those given above, are very useful for obtaining a general idea of the amount of the increase of temperature, they should be used with discretion, and it should be well understood that the rise of temperature is greatly modified by various circumstances, such as:

Field-magnet coils—depth of winding; accessibility of air to surface of spools; force with which air is driven against spool surfaces; shape and extent of magnet cores on which coils are located; season, latitude, nature of location, *i.e.*, whether near boiler-room or in some unventilated corner, or in a large well-ventilated station, or under a car, &c.

Armature windings and cores—similar variable factors, particularly method and degree of ventilation; shape and details of spider; centrifugal force with which air is urged through ventilating ducts; degree of freedom from throttling in ducts; number of ducts; freedom of escape of air from periphery; and peripheral speed. Thus it will be readily understood that the values for rise of temperature per watt per square inch have to be determined from a number of conditions.

Small machines quickly reach the maximum temperature; large machines continue to rise in temperature for many hours. Hence the length of a heat run should be decided upon with reference to the nature of the apparatus and the use to which it is to be put. The heat should be distributed in proportion to the thermal emissivity of each part, with due regard to the permissible rise of temperature. Heating is of positive advantage, in so far as it is limited to temperatures that will keep the

insulation thoroughly dry, and thus tend to preserve it. But it is disadvantageous as regards preservation of insulation, in so far as it overheats and deteriorates it. The permissible temperature is thus dependent upon the nature of the insulation. In railway motors, the field conductors are often insulated with an asbestos covering, as the location of the motors does not permit of their being sufficiently large to run cool under heavy loads.

Magnets

The radiating surface of magnets of ordinary design, *i.e.*, those in which the diameter of the magnet coil approximately equals the length, is ordinarily taken to be the cylindrical surface, no account being taken of the ends, which in general are not very efficient for the radiation of heat; when, however, the magnets are very short, and the surface of the ends large, they should be considered.

Armatures

As radiating surface of the armature, one should, strictly speaking, take the sum of the bounding surfaces of all those parts which are directly exposed to the air, and in which heat is generated.

Allowance should be made for the different linear velocities of different portions of the armature windings. Thus in the ordinary Siemens type of armature the radiation per square inch, or thermal emissivity, at the ends, averages only about two-thirds that at the cylindrical surface, the difference being due to the difference in surface speed. In the case of armatures of very large diameter, the thermal emissivity at the ends becomes approximately equal to that of the cylindrical portion when the armatures are not very long. When the armatures have a length approaching half the diameter of the armature, the thermal emissivity at the ends may considerably exceed that midway between the ends of the armatures, unless special means for ventilating are resorted to.

In the "barrel" type of winding, now largely used, the end connections are approximately in the same cylindrical surface as the peripheral conductors, being supported upon a cylindrical extension from the spider. Here the entire armature winding revolves at the same peripheral speed, and is in the best position as regards ventilation.

The radiation of heat from an armature is not affected greatly by varying the surface of the pole-pieces, within the limits attained in ordinary

practice. If, however, the magnets are rectangular in section, and placed closely together, the radiation of heat from the armature may be considerably restricted. Further, unless the magnets are so placed with respect to each other that the heat of each is carried off independently of that of the others, special means for ventilating will have to be resorted to, and the values given above will not hold. Such constructions as the last two mentioned are not recommended for general practice.

Example of Estimation of Temperature Rise

Diameter of a certain ironclad armature	= 35 in.
Length, over winding	= 25 „
Speed	= 360 revs. per min.
Internal diameter	= 18 in.
$35 \times \pi \times 25$	= 2750. sq. in.
$18 \times \pi \times 25$	= 1420. „
$\frac{\pi}{4} \times (25^2 - 18^2) \times 2$	= 470. „
Total radiating surface	= 4640. „

$$\text{Peripheral speed} = \pi \times \frac{35}{12} \times 360. = 3300. \text{ ft. per min.}$$

If well ventilated by internal ducts, it should be very safe to take 22 deg. Cent. rise of temperature per watt per square inch.

	Watts.
Core loss	5000
Armature C^2 R	2600
Total loss	7600

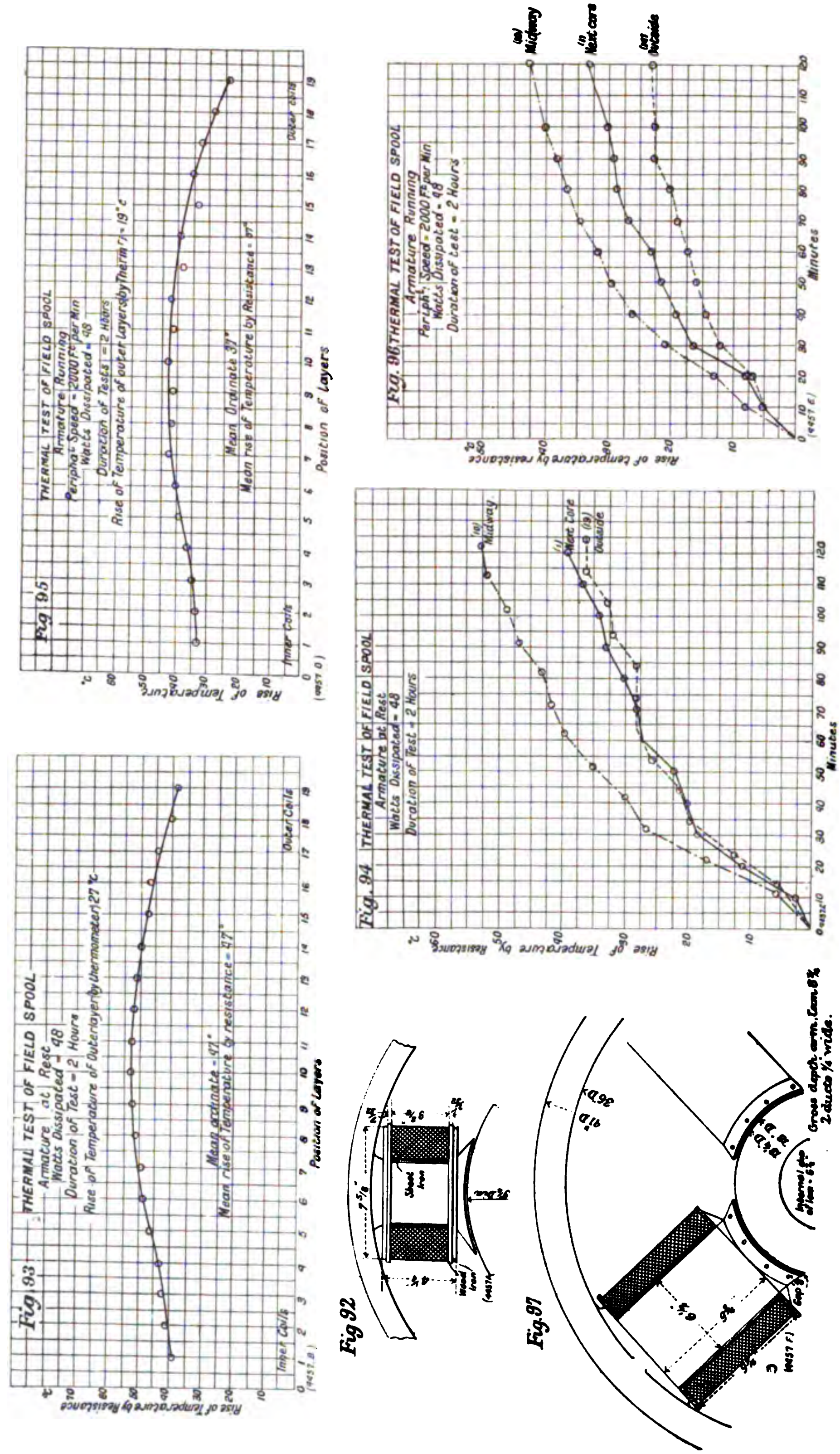
$$\therefore \frac{7600}{4640} = 1.64 \text{ watts per square inch.}$$

$\therefore 1.64 \times 22 \doteq 36$ deg. Cent. rise of temperature at end of 10 hours run at full load.

Internal and Surface Temperature of Coils

The importance of determining the internal temperature of coils by resistance measurements, instead of relying upon the indications of a thermometer placed upon the surface, is well shown by the results of the following test. An experimental field-magnet coil was wound up with 2646 total turns of No. 21 B.W.G., the winding consisting in 38 layers, from every pair of which separate leads were brought out, to enable the temperature of all parts of the coil to be determined by resistance measurements.

Two distinct tests were made, one with the armature at rest, and the



FIGS. 92 TO 97. THERMAL TESTS OF A FIELD SPOOL

other with the armature running at a peripheral speed of 2,000 ft. per minute. Each test lasted two hours, the current through the coil being maintained constant at one ampere throughout both tests. Every ten minutes a reading was taken on a voltmeter across each pair of layers, thus giving a record of the change in resistance as the test progressed. A dimensioned sketch of the coil, pole-piece, and armature is given in Fig. 92, and the results of the tests are plotted in the curves of Figs. 93 to 96.

For the armature at rest, Fig. 93 shows the ultimate rise of temperature in the different layers plotted against the positions of those layers; and Fig. 94 shows the rise of temperature in the innermost layers, the middle layers, and the outside layers, plotted against time.

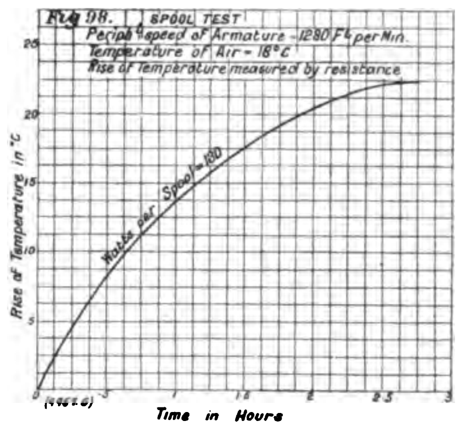


Fig. 98. Thermal Test of a Field Spool

The curves show well that without the aid of the circulation of air set up by the rotation of the armature, the metal of the field-magnet core is as effective in carrying away the heat, as is the air which bathes the surface of the spool. For the armature running at a peripheral speed of 2,000 revolutions per minute, the results are plotted in the curves of Figs. 95 and 96. The latter figure shows that with the circulation of air set up by the rotation of the armature, the outside of the coil is maintained much cooler than is the inner surface adjoining the field-magnet core. But the most significant conclusion to be drawn from the tests is that shown by Figs. 93 and 95, namely, that the temperature of the interior layer of a coil may considerably exceed that corresponding to the average rise of resistance of the total winding.

In Figs. 97 and 98 are given respectively a sketch of the field-magnet and spool of a machine, and the result of a heat test taken upon it, in

which the average temperature of the field spools was determined from time to time, by means of resistance measurements of the field winding.

The influence of the peripheral speed of the armature upon the constants for determining the temperature increase of field spools, as well as the effect of covering the wire with a final serving of protecting cord, are clearly shown by the results of the following test made upon the

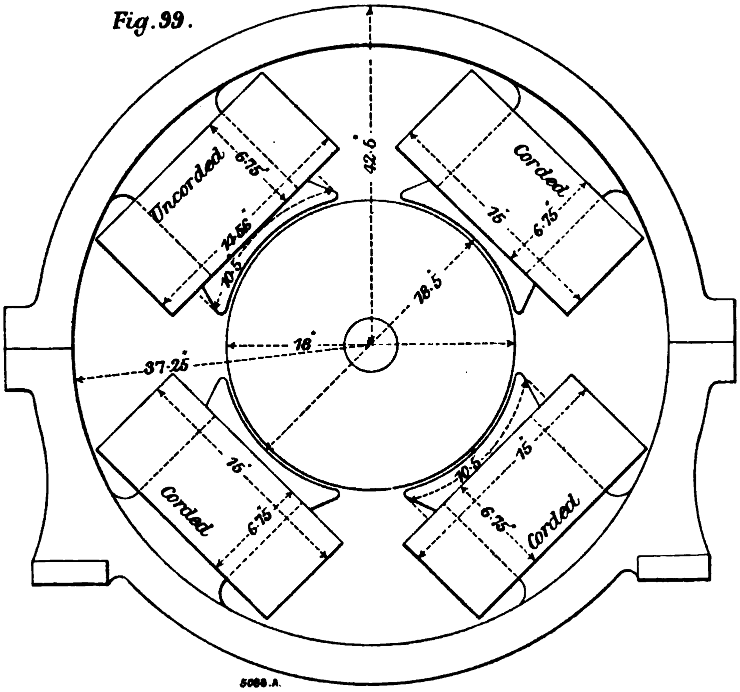


Fig. 99. Sketch of Machine Tested

field spools of a continuous-current generator of 35 kilowatts rated output.* The tests were made with a wide range of field excitation, and the temperatures were determined both by thermometric and resistance measurements. The results afford a check upon the more general values given on page 94 for predetermining the temperature rise of spools. In Fig. 99 is given a dimensioned sketch of the machine, and in Figs. 100 to 111 are curves of results of the various heat runs. The curves of Fig. 112 summarise the average results obtained (see pages 102 to 105).

* See "Rise of Temperature in Field Coils of Dynamos," by E. Brown (*Journal*, Institution of Electrical Engineers, vol. xxx., pages 1159 to 1199, August, 1901); and "Report on Temperature Experiments, carried out at the National Physical Laboratory," by E. H. Rayner; paper read by Dr. Glazebrook before the Institution of Electrical Engineers, March 9th, 1905. See also the very interesting paper, "Temperature Curves and the Rating of Electrical Machinery," read by R. Goldschmidt before the Institution of Electrical Engineers, March 9th, 1905.

Out of the four field spools, two only were under observation, *i.e.*, the top two. On one of these two spools the cording and insulation were taken off, and the winding exposed directly to the air; the other spools remained corded. For the purpose of measuring the outside temperature of the spools, thermometers were placed, for the one spool on the outside of the winding and for the other spool on the outside of the cording; the third temperature measurement was determined from the resistance increase of the four spools in series. Thus, three temperature measurements were made :—

1st. On the outside of the uncorded spool, by thermometer.

2nd. „ „ corded „ „

3rd. Increase of temperature of the four spools by resistance.

The four spools were connected in series, the amperes input being kept constant, and the volts drop across the four spools noted.

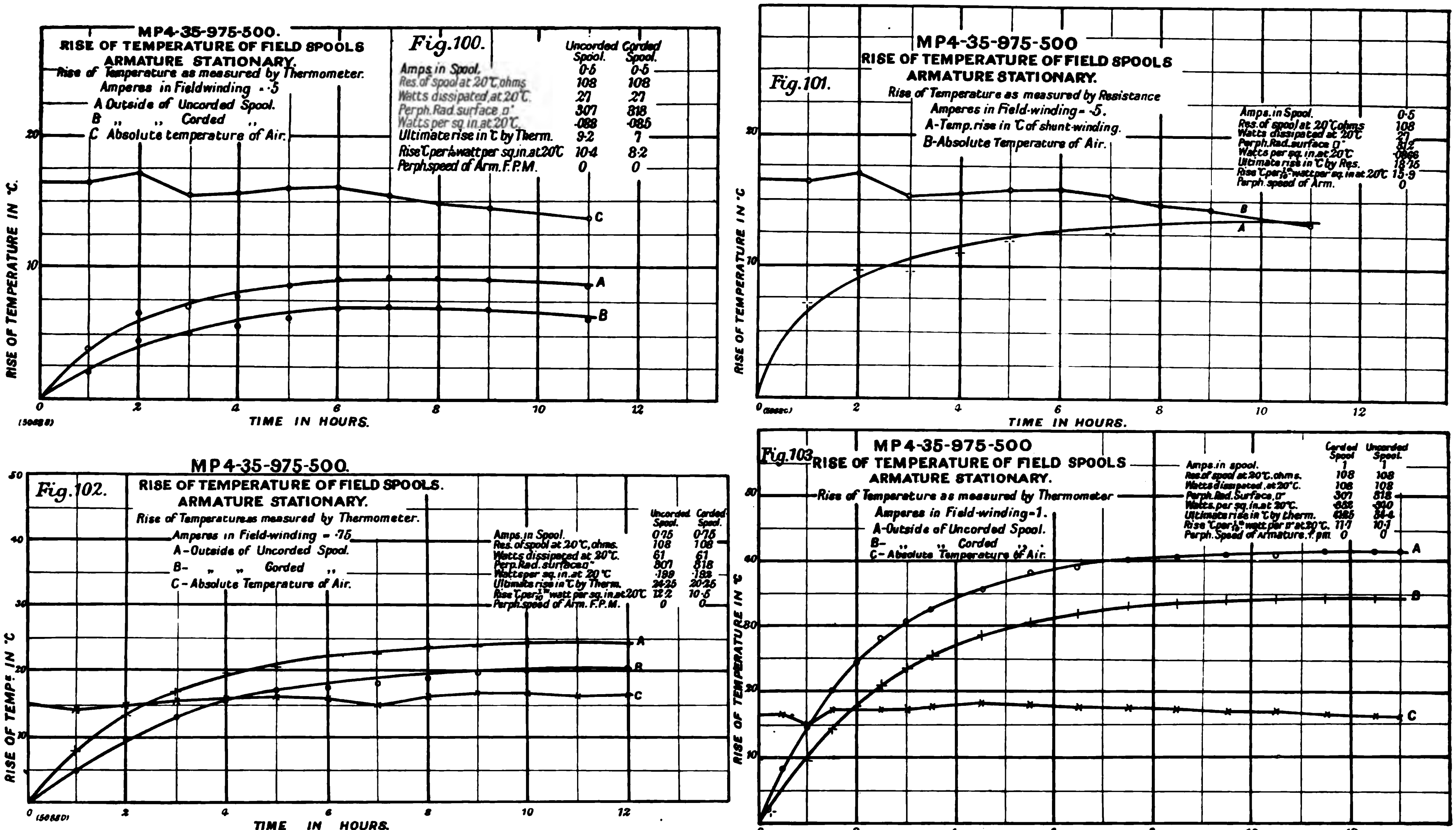
In the first case, the armature remained stationary, and results were obtained with .5, .75 and 1 ampere. These results are set forth in the curves of Figs. 100 to 105.

The armature was then revolved at a peripheral speed of 2000 ft. per minute, and temperature rises observed at .75, 1 and 1.25 amperes. In this case, a different procedure was adopted. On the temperature reaching a constant value with .75 ampere, the test was carried on, the amperes being raised to 1, and again, after reaching a constant value, to 1.25 amperes. At this point the temperature reached a value above which it was not advisable to go. Results of this test are set forth in the curves of Figs. 106 and 107.

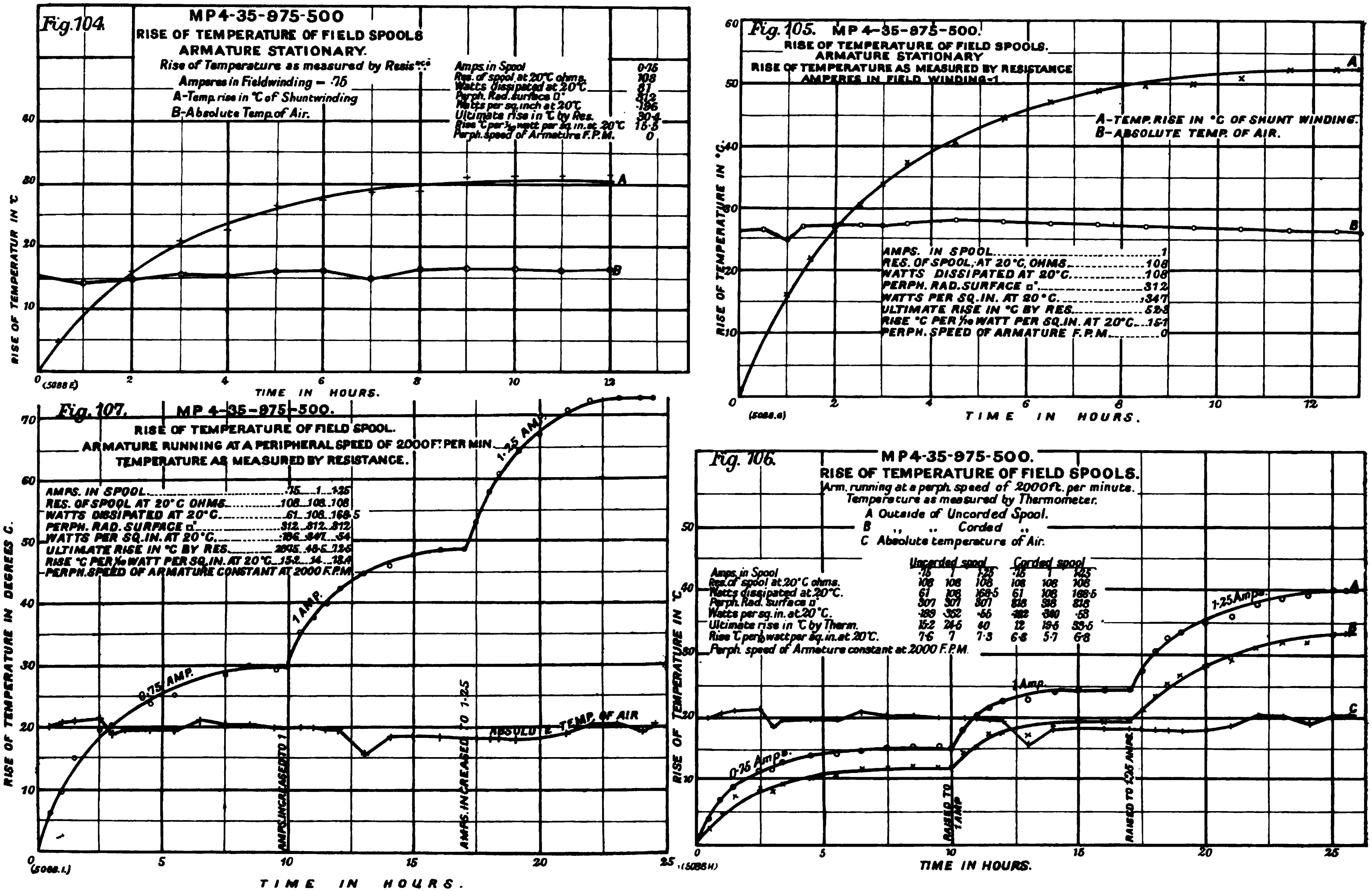
Two further tests were carried out on similar lines, at peripheral speeds of 3500 ft. and 4800 ft. per minute, results of which are set forth in the curves of Figs. 108 to 111.

From the curves of Fig. 112, in which the average results of all these tests are summarised, it will be noted that a considerable increase of speed above 2000 ft. per minute does not, for this machine, reduce the temperature rise to any very great extent.

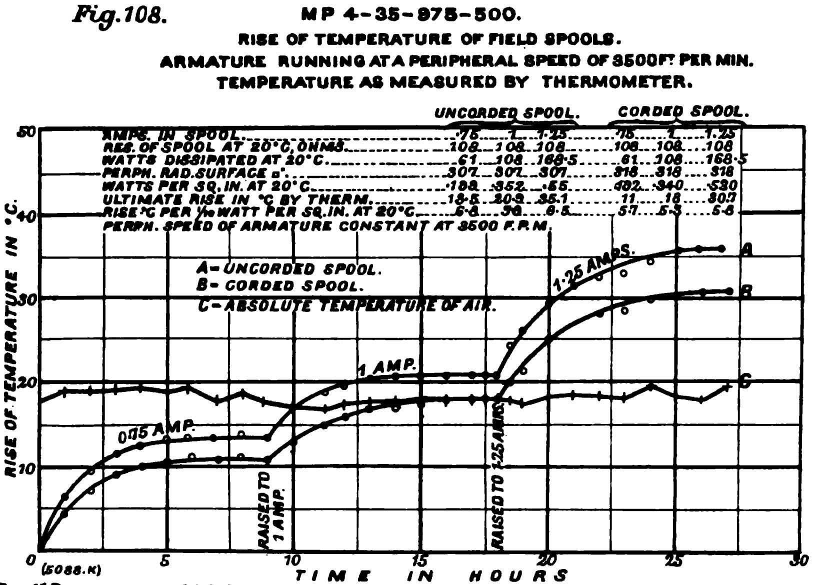
On each of the curves a table is given, setting forth the working data, and the constants derived from the tests. It will be noted that the results are figured from the assumption that the watts dissipated remain constant, whereas in reality they vary as the temperature alters; but as this variation would complicate the calculations, these are based on the resistance at 20 deg. Cent., namely, 108 ohms per spool.

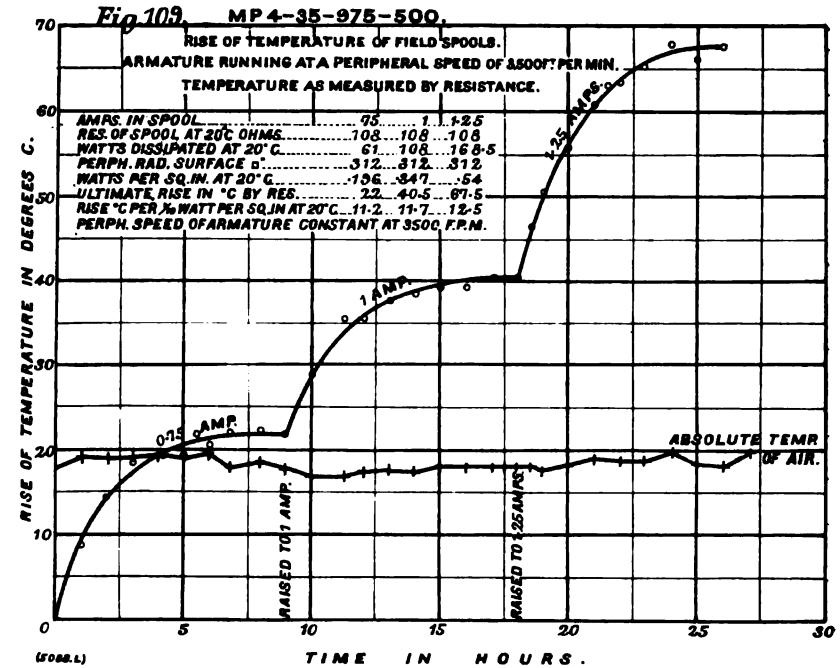


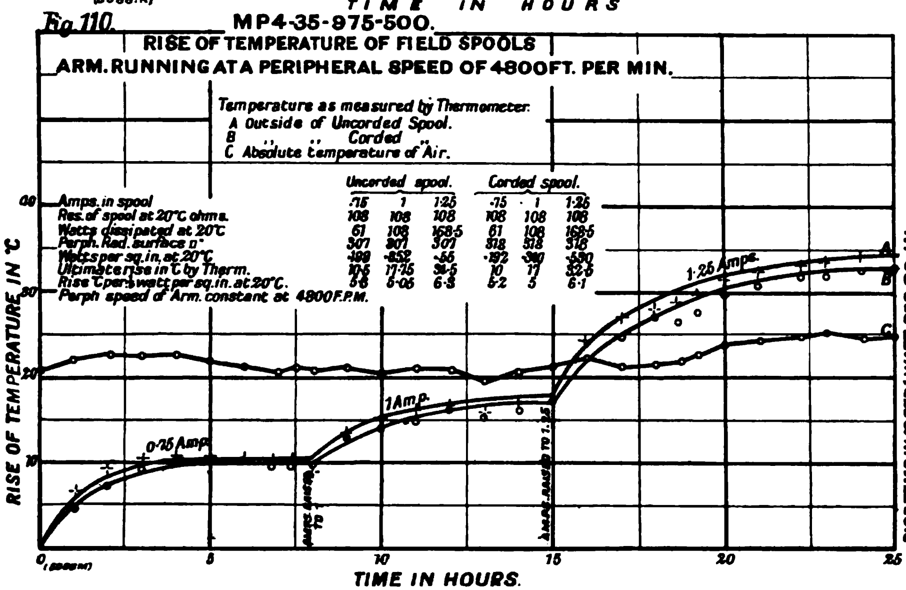
FIGS. 100 TO 103. THERMAL TEST CURVES

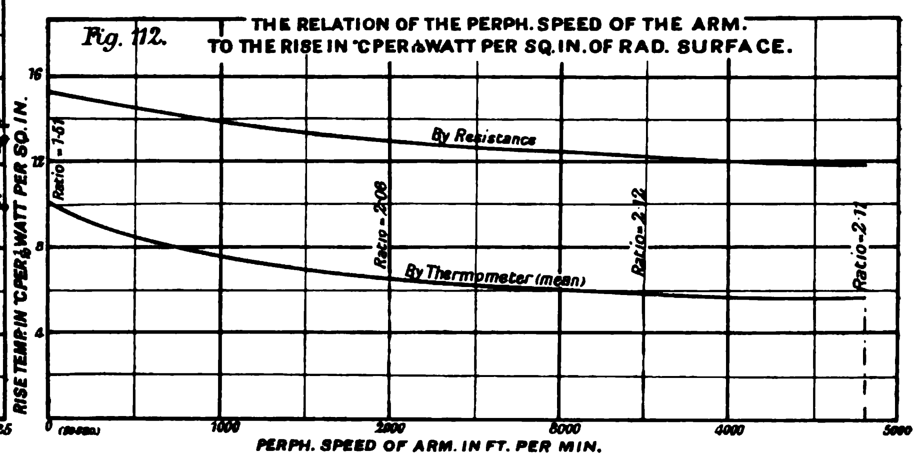


FIGS. 104 TO 107. THERMAL TEST CURVES









FIGS. 108 TO 110, AND 112. THERMAL TEST CURVES

The peripheral radiating surfaces of the two spools differ, owing to the cording having been removed in the one case; therefore, in figuring on the thermometer measurements of the corded and uncorded spools, their respective radiating surfaces are used; but in the case of the measurements of temperature rise by resistance, a mean peripheral radiating surface is taken.

It should furthermore be noted that the higher the peripheral speed of the armature, the less is the difference between the temperature rise observed from thermometric readings on the surfaces of the corded and the uncorded spools.

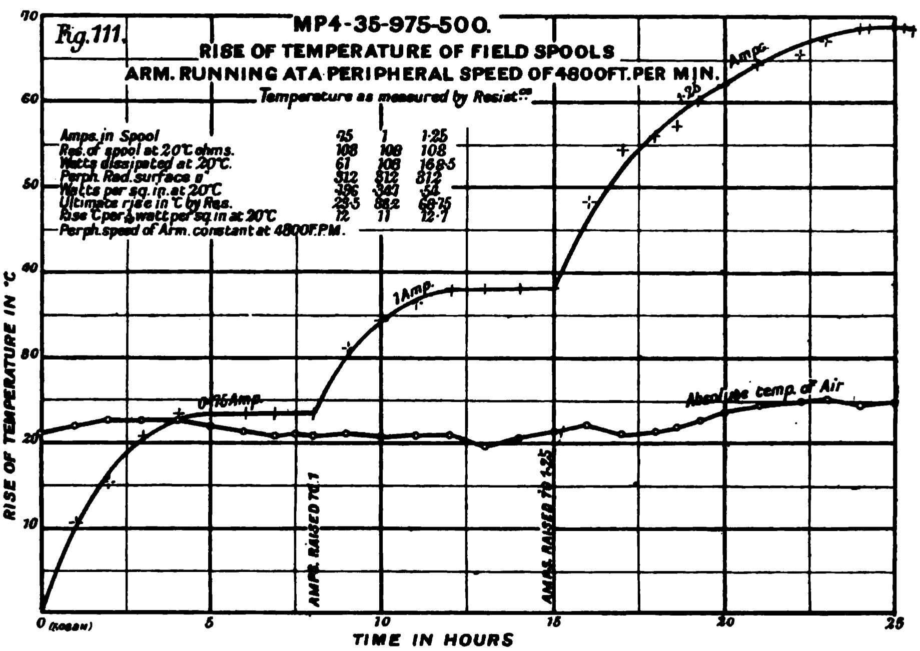


FIG. 111. THERMAL TEST CURVES

The armature had two ventilating ducts, each one half-inch wide, through which air was thrown out centrifugally, after entering through the open end of the armature spider.

HEAT LOSSES—C^2 R DUE TO USEFUL CURRENTS IN THE CONDUCTORS

Heat generated, due to the current and resistance, is calculated directly from these two factors. The resistances should be taken to correspond to the temperature the conductors attain in practice To determine this temperature, resistance measurements are much more reliable than thermometric measurements. For standard sizes of wire,

the resistance is most conveniently determined by ascertaining from Tables the ohms per 1000 ft. of the size of wire in question. Then the length of wire in the magnet spool or armature, as the case may be, should be computed from the number of turns and the mean length of one turn. The total resistance can then be obtained.

The Appendix contains Tables of this description, which give the properties of commercial copper wire for three standard gauges, namely, B. and S. (American); S.W.G. (Board of Trade); and B.W.G. (Birmingham Wire Gauge). They have been arranged with especial reference to convenience in designing electrical apparatus, but they do not differ greatly from the Tables arranged for exterior wiring and other purposes. They serve as a basis for thermal calculations, and are also useful in the calculation of spool windings, as considered in the section on the design of the magnetic circuit.

Example.—A certain transformer has, in the primary, 1200 turns of No. 7 B. and S. Mean length of one turn = 28 in. = 2.33 ft. Total length = 2.33 × 1200 = 2800 ft. No. 7 B. and S. has (see Table in Appendix), at 20 deg. Cent., .497 ohms per 1000 ft. Therefore, the primary resistance at 20 deg. Cent. = 2.8 × .497 = 1.40 ohms. Suppose full load current = 13 amperes. Then the primary $C^2 R$ = 169 × 1.40 = 237 watts.

Specific resistance of commercial copper at 0 deg. Cent.

= .00000160 ohms per cubic centimetre.
= .00000063 ohms per cubic inch.

i.e., between opposite faces of a cubical unit. The above constants are of use when other than standard sizes of wire are employed. In connection with them it should be kept in mind that the resistance of copper changes about .39 per cent. per deg. Cent. Where more convenient, and where greater accuracy is desired, use may be made of the following factors, by which the resistance at 0 deg. Cent. should be multiplied in order to obtain the resistance at the temperature employed :—

TABLE XXIX

0	1.000
20	1.080
40	1.160
60	1.250
80	1.337
100	1.422

Example.—An armature has a conductor .60 in. by .30 in. = .180 square inches in cross-section. It has an eight-circuit double winding. Total turns = 800. Mean length of one turn = 60 in. Turns in series between brushes $= \frac{800}{8 \times 2} = 50$. Therefore, length of winding between positive and negative brushes = 50 × 60 = 3000 in. Cross-section = 8 × 2 × .18 = 2.88 square inches. Therefore, resistance at 0 deg. Cent. $= \frac{3000 \times .00000063}{2.88} = .000655$ ohms. Suppose the full-load current of 4000 amperes heats the armature conductors to 60 deg. Cent. Then the armature C^2 R at 60 deg. Cent. $= 4000^2 \times .000655 \times 1.25 = 13{,}100$ watts.

The Tables of properties of commercial copper wire are supplemented by a Table in the Appendix, giving the physical and electrical properties of various metals and alloys. This Table, used in connection with the others, permits of readily determining resistances, weights, dimensions, &c. of various conducting materials.

Foucault Currents

In addition, to the C^2 R losses in the conductors, there are losses due to parasitic currents, often termed eddy or Foucault currents, when solid conductors, if stationary, are exposed to the influence of varying induction from magnetic fields; and whenever they are moved through constant magnetic fields, except in cases where the solid conductors are shielded from these magnetic influences.

In armatures with smooth-core construction, the conductors are not screened from the magnetic field, consequently there may be considerable loss in the conductors from Foucault currents. This loss has been found to vary greatly, according to the distribution and density of magnetism in the air gap, and cannot be accurately predetermined.

In practice this loss is kept as small as possible; in the case of bar windings, by laminating the bars and insulating them from each other; or in the case of wire windings, by using conductors $\frac{1}{16}$-in. or less in diameter, and twisting these into a cable. The amount by which the Foucault current loss can be lessened in this last method is forcibly illustrated by the following example: The winding of a certain armature consisted of four wires in parallel, each 0.165 in. in diameter. These conductors were replaced by nineteen strands of cable having the same cross-section

of copper, and the total loss of the armature was diminished by one-third.

In iron-clad dynamos, the conductors are more or less protected from eddy currents by being embedded in slots. This exemption from such losses depends upon the extent to which the teeth overhang, and upon the density in the teeth; very high density throwing part of the lines through the slots, instead of permitting them all to be transmitted along the teeth. Even where the tooth density is low, stranded conductors must sometimes be used in iron-clad armatures. As an instance may be cited the case of an alternating current armature, with a slot of the proportions shown in Fig. 113. Here solid conductors of the proportions shown were at first used, but the cross-flux set up by the armature current was perpendicular to the plane of the conductors, and excessive heating resulted from the eddy currents set up in the solid conductors. Stranded conductors should be used in such a case.

Stranded conductors are open to the objections of increased first cost, and of having from 15 per cent. to 20 per cent. higher resistance for given outside dimensions. This increased resistance is not entirely due to the lesser total cross-section of the component conductors, but also partly to their increased length, caused by the twist given them in originally making up the conductor. The stranded conductor, constructed, in the first place, with a circular cross-section, is pressed to the required rectangular section, in a press operated by hydraulic pressure. No precautions, such as oxidising, or otherwise coating the surface of the component wires, are necessary. The mere contact resistance suffices to break up the cross-currents.

Closely related to the losses just described are the eddy-current losses in all solid metal parts subjected to inductive influences. This occurs chiefly in pole-faces; but if the proportions of the armature are such that, in passing the pole-pieces, the reluctance of the magnetic circuit is much varied, eddy currents will be found throughout all solid parts of the entire magnetic circuit. Consequently, in such cases, not only the pole-pieces but the entire magnetic yoke should be laminated. Such a construction has been used in alternators, with the result that, especially in the case of uni-slot armatures, a very marked improvement has been made in efficiency and in heating.

In continuous-current machines, the surface of the armature is broken up by a large number of small slots, and the disturbance is mainly local, the

reluctance of the magnetic circuit, as a whole, remaining unchanged. Nevertheless, in such cases, the loss in the neighbourhood of the pole-face may be large, and will be found to depend chiefly upon the depth of the air gap as related to the width of the slot opening. Instances have occurred in small machines, where increasing the depth of the air gap from $\frac{1}{8}$ in. to $\frac{1}{4}$ in. has greatly modified the magnitude of such pole-face losses. Straight-sided armature slots give, of course, much greater losses in the pole-face than slots with overhanging projections; while if the slots are completely closed over, the loss is practically eliminated.

Pole-faces frequently consist of a laminated structure, cast in, or sometimes bolted on, to the upper portion of the magnet core. Another

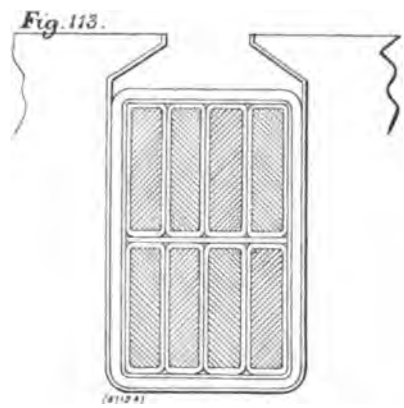


FIG. 113. ARMATURE SLOT OF A LARGE ALTERNATOR

type of construction consists in laminating the entire magnet core, and casting it into the solid yoke.

In the neighbourhood of conductors and coils which are the seat of high magnetomotive forces, solid supports, shields, and the like, should be avoided, unless of high resistance, non-magnetic material, such as manganese steel. For this reason, spool flanges could also well be made of manganese steel.

Eddy-current losses in the sheets of armature cores are dependent upon the square of the density of the flux, the square of the periodicity, and the square of the thickness of the sheets. Also, upon the care with which the laminations are insulated from each other. It is, therefore, important to avoid milling and filing in slots, as this tends to destroy the insulation, and makes a more or less continuous conductor parallel to the copper conductors. Consequently, the eddy-current loss is quite largely

dependent upon the relative magnitudes of flux, number of turns, and length of armature parallel to the shaft, as upon these quantities depends the voltage per unit of length tending to set up parasitic currents in the armature core. Owing to the less amount of machine work, smooth-core armatures are much more apt to be free from parasitic currents in the core. The more such losses from eddy currents are anticipated from the nature of the design, the greater should be the safety factor applied to the value of the core loss as derived from the curves of Figs. 39 and 40 (see page 37).

Armature punchings should, when possible, be assembled without any milling or filing. Cases are on record where the milling of armature slots

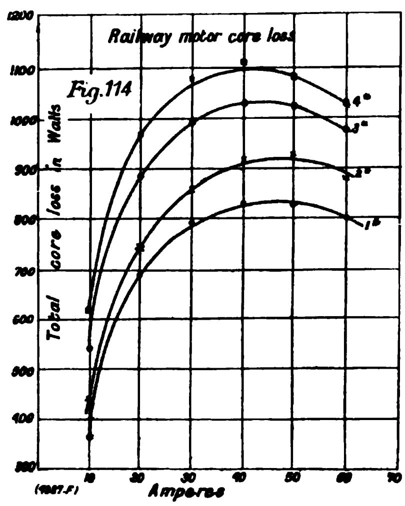


FIG. 114. CORE LOSS CURVES

has increased the core loss to three times its original value, the metal removed by milling being merely a thin layer from the sides of the slot. Even light filing increases the core loss considerably. Most of the increase, in both these cases, is due to the burring of the edges making a more or less continuous conductor, although there is also a slight increase due to injuring the quality of the iron by mechanical shock.

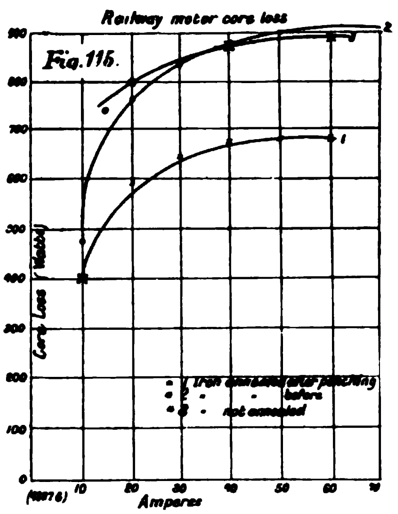
In a modern railway motor, this matter was studied by testing the core loss at various stages of the process of manufacture. The curves of Fig. 114 represent the average results from tests of two armatures.

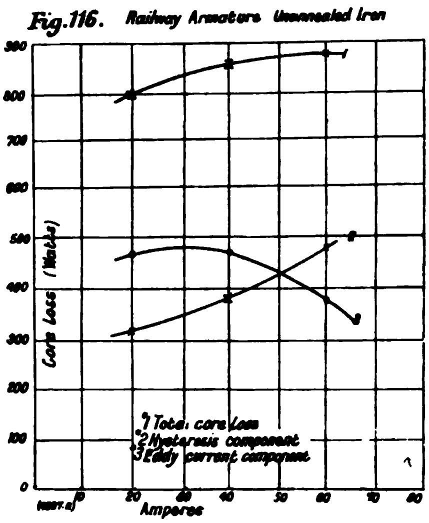
Curve	1	was taken after	assembling the punchings.
,,	2	,,	teeth were wedged straight.
,,	3	,,	slots were slightly filed.
,,	4	,,	winding.

The difference between curves 3 and 4 gives the eddy-current loss in the conductors. The particular shape of the curves possesses no especial significance in connection with the object of the investigation, and is merely due to the armature having been driven at the various speeds corresponding to the conditions of practice for the corresponding values of the current.

Hysteresis Loss in Cores

The hysteresis loss in armature cores may be estimated directly from curve A of Fig. 39 (page 37), which represents the magnetic grade of iron generally used in armature construction. However, the temperature of





FIGS. 115 AND 116. CORE LOSS CURVES

annealing, and the subsequent treatment of the iron, materially influence the result.

In Fig. 115 are given three curves of total core losses of three railway motor armatures.

Curve 1. Iron annealed after punching.

Curve 2. Iron annealed before punching.

Curve 3. Iron not annealed.

Nevertheless, it is very likely that in the case of a railway motor armature, the rough conditions of service soon largely destroy any temporary gain from annealing subsequent to punching.

In Fig. 116 the total core loss in the armature with unannealed iron has been analysed, and the hysteresis and eddy-current components

TABLE XXX.—DIMENSIONS AND OBSERVED CORE LOSSES OF TWENTY-THREE COMMUTATING GENERATORS.

(SEE FIG. 117.)

Type of Generator.	Rated Output in Kilowatts.	Number of Poles.	Speed, Revolutions per Minute.	Date of Construction.	External Diameter of Armature. (A.)	Internal Diameter of Armature Laminations. (B.)	Depth of Armature Slot. (C.)	Width of Arm Slot. (D.)	Width of Tooth at Root. (E.)	Width of Tooth at Arm Face. (E'.)	Depth of Laminations below Slot. (F.)	Gross Width of Core. (G.)	Effective Width of Core.	Ratio of Pole Arc to Pitch.	Number of Slots.	Megalines Flux Entering Armature per Pole.	Number of Teeth Assumed to Transmit Flux per Pole.	Apparent Density at Root Teeth in Kilolines.	Density below Slots in Kilolines.	Total Observed Core Loss in Watts.	Weight of Laminations below Slots.	Weight of Teeth.	Total Weight of Laminations.	Watts of Core Loss, per Pound.	Cycles per Second = C.	Kilolines of Density below Slots = D.	$\frac{CD}{1000}$.	K. $\left(\frac{CD}{1000} \times K = \text{Watts per Pound}\right)$.
					in.	in.	in.	in.	in.	in.	in.	in.	in.								lb.	lb.	lb.					
Railway ..	300	6	100	1897	59.25	38.5	1.688	.58	.467	.580	8.7	21.25	16.9	.68	168	25.6	21	154	87	5,350	6100	660	6,760	.79	5.00	87	.435	1.82
Lighting ..	225	8	85	1898	59.25	42.5	1.75	.49	.507	.578	8.5	18.125	14.6	.67	160	13.9	15	125	56	2,260	4250	620	4,870	.47	5.66	56	.318	1.48
Railway ..	385	8	90	1898	72	53.15	1.8	.6	.481	.5425	7.625	24.75	18.9	.742	198	23.95	20	137.2	83.2	9,300	7770	965	8,735	1.06	6.00	83.2	.499	2.12
Railway ..	225	6	120	1898	59.25	38.5	1.625	.416	.382	.4275	8.75	16.25	12.375	.642	220	16.4	26	138	75.7	3,265	4530	493	5,023	.65	6.00	75.7	.454	1.43
Railway ..	525	8	100	1898	72	53.125	1.762	.368	.321	.357	7.68	25.25	20.0	.73	312	27.3	31	137	89	7,600	8300	1050	9,350	.81	6.66	89	.595	1.36
Railway ..	200	6	135	1898	59.25	38.5	1.625	.416	.384	.429	8.75	14.25	9.9	.74	220	13.3	29	129	76	2,760	3603	400	4,000	.69	6.75	76	.513	1.35
Railway ..	300	6	150	1897	53	31.54	1.7	.33	.329	.374	9.03	23	11.238	.76	236	24.04	32	128.2	73	5,270	5720	724	6,644	.794	7.50	73	.547	1.45
Power.. ..	225	6	150	1897	59.25	38.5	1.625	.44	.437	.490	8.75	16.75	12.825	.65	200	13.08	24	100.8	58.3	4,150	4690	545	5,235	.794	7.50	58.3	.437	1.82
Railway ..	500	10	90	1898	88.5	68.1875	1.8	.666	.445	.490	10.2	18.5	16.3	.69	240	19	19	146	61	9,250	8650	880	9,530	.97	7.50	61	.457	2.12
Railway ..	150	6	150	1898	43	28.75	1.5	.42	.396	.457	8.125	15.25	11.9	.70	154	12·5	20	133	65	2,510	2350	330	2,680	.94	7.50	65	.487	1.93
Power.. ..	500	8	120	1898	72	53.1	1.73	.445	.346	.386	7.72	27.625	22.05	.76	272	3.09	28	149.5	90.9	10,670	9170	1078	10,240	1.04	8.00	99.9	.727	1.43
Railway ..	400	8	120	1898	66	46.75	1.625	.44	.383	.424	8	18.125	14.6	.78	240	18.1	25	130	78	5,480	5660	650	6,300	.87	8.00	78	.625	1.39
Lighting ..	300	10	100	1897	32.625	25.44	1.75	.59	.478	.539	5.44	17.625	12.7	.65	180	11.1	14	130	78	4,050	3500	560	4,060	1.00	8.33	78	.650	1.54
Power.. .	100	8	150	1897	45.125	34.25	1.3125	.45	.354	.405	4.13	12.125	10	.76	167	7.75	18	122	94	3,300	1400	230	1,630	2.02	10.00	94	.940	2.14
Lighting ..	300	10	140	1898	59.25	38.49	1.48	.52	.363	.4075	8.90	14.75	11.925	.699	200	7.91	16	121.1	37.3	3,210	4480	364	4,844	.664	11.70	37.3	.436	1.52
Lighting ..	100	6	250	1897	31.5	19.66	1.5	.44	.374	.458	4.42	12	9.11	.788	110	7.05	16	137	87.6	2,010	860	176	1,036	1.94	12.50	87.6	1.09	1.17
Power.. ..	560	6	300	1896	59.25	37.4	1.625	.58	.465	.524	9.3	14.5	11.0	.67	168	16.6	21	144	77	12,520	4460	511	497	2.52	15.00	77	1.15	2.18
Lighting ..	160	8	230	1898	45.125	34.25	1.3125	.474	.333	.385	4.125	9.5	7.875	.67	165	5.22	16	132	80.3	2,230	1100	170	1,270	1.75	15.35	80.3	1.23	1.42
Railway ..	325	6	400	1897	45	30.684	1.178	.412	.284	.023	5.98	15	11.8125	.715	192	11.05	24	141	78.3	7,800	2295	240	2,535	3.08	20.00	78.3	1.56	1.96
—	—	12	250	1899	84	62	1.25	.44	.449	.475	9.75	12.5	9.9	.722	288	10.4	17	134	54	19,850	6500	500	7,000	2.8	25.0	54	1.35	2.08
Power.. ..	110	6	600	1898	28	17.5	1.6	.342	.258	.335	3.65	7.25	6.1875	.75	130	3.63	18	134.6	80.4	2,335	424	106	530	4.41	30.00	80.4	2.41	1.83
Rot. Converter	200	6	600	1898	30	16.55	1.30	.32	.364	.4275	5.423	9	6.75	.733	126	5.16	17	132	70.4	2,725	711	124	835	3.26	30.00	70.4	2.11	1.54
Railway ..	100	6	600	1897	26.5	17.75	1.312	.37	.230	.296	3.06	8.5	7.38	.68	125	3.75	16	138	83	2.420	425	90	515	4.70	30.00	83	2.49	1.89

are shown in curves Nos. 2 and 3, the resultant loss being given in curve No. 1.

In determining the core losses of electric generators, it is frequently convenient to resort to empirical devices, as a check upon more theoretical

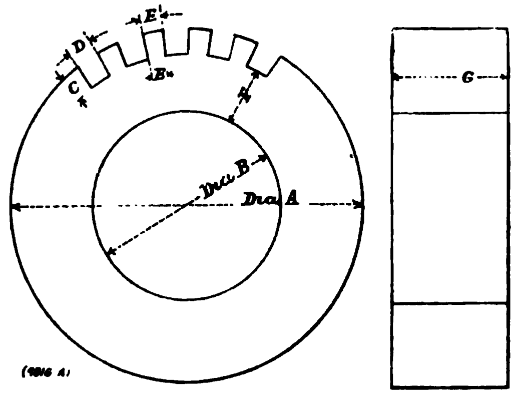


Fig. 117. Diagrammatic Sketch of Armature Core

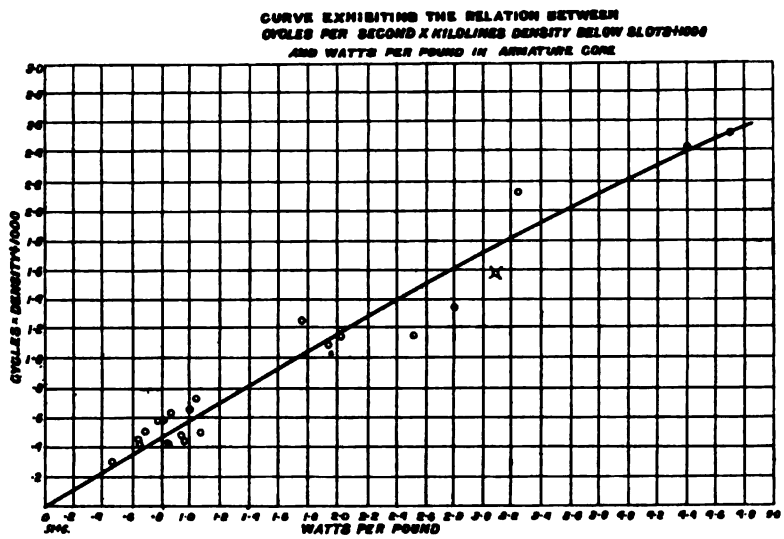
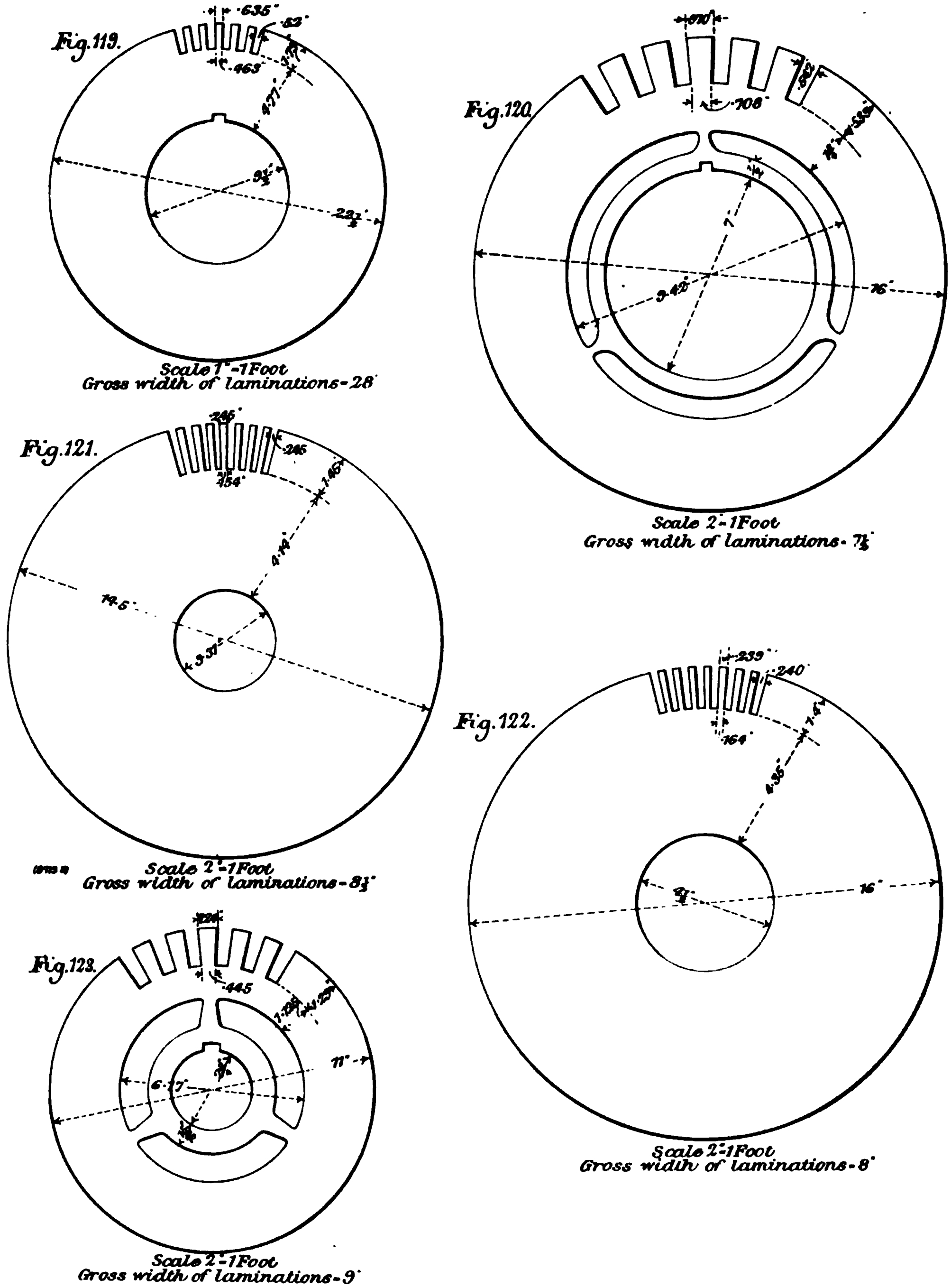


Fig. 118. Core Loss Curve

Observations made on Twenty-three Large Continuous-Current Generators

methods, owing to the conditions in practice affecting the results. As already explained, the machine-work upon the armature, the periodic variations in the magnetic reluctance, with resulting eddy current and hysteretic losses in the magnet frame, and the eddy currents in the armature conductors, supports, shields, &c., all tend to introduce uncertain factors.



FIGS. 119 TO 123. LAMINATIONS OF THE FIVE RAILWAY MOTORS ON WHICH THE TESTS SHOWN IN FIG. 124 WERE MADE

Table XXX. gives the dimensions and the observed core losses of twenty-three large multipolar commutating machines, in the design of which there was a wide range of periodicities and magnetic densities. The letters A to G in the headings of the first columns of Table XXX. refer to those in Fig. 117, which is a sketch for an armature core. The results set forth in this Table are useful in drawing practical conclusions as to the probable core losses of new designs. Although in these designs the rate of dissipation of energy in the teeth is high, the small percentage which the mass in the teeth bears to the total mass of the core of the armature makes it practicable, as shown by the results given in the Table, to draw conclusions from a comparison of the

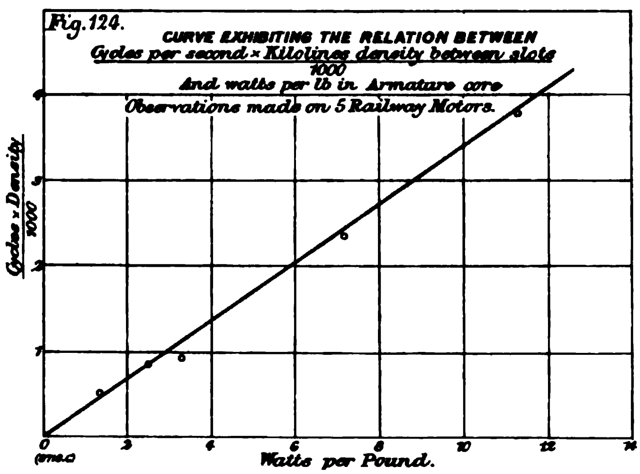


FIG. 124. CORE LOSS CURVE, RAILWAY MOTORS

watts per pound of total laminations as related to the periodicity and to the density below slots. But this would not be found to be the case, except when tooth densities are chosen, lying within the limits generally adopted, since the higher the density in the projections, the more considerable is the loss due to eddy currents in the embedded copper conductors, owing to the stray field crossing them. One would, therefore, expect in railway motors where the weight of the teeth is a larger percentage of the total weight, and where the densities are considerably higher, that relatively higher values for the *apparent* core losses would be found. The authors have therefore given, in Table XXXI., an analysis based on five railway motors, sketches of the laminations of which are given in Figs. 119 to 123. Another factor affecting the value of the core loss in commutating dynamos is the influence of the conditions during commuta-

TABLE XXXI.—ANALYSIS OF CORE LOSSES OF RAILWAY MOTORS.

Figure Numbers.	Number of Poles.	Rated Output, Horse-Power.	Speed, Revolutions per Minute at Rated Output.	Terminal Voltage, Full Load.	Counter Electromotive Force of Motor.	External Diameter of Armature.	Internal Diameter of Armature Laminations.	Depth of Armature Slot.	Width of Armature Slot.	Width of Tooth at Root.	Width of Tooth at Armature Face.	Depth of Laminations below Slots.	Gross Width of Armature Laminations.	Width of Vent Ducts.	Number of Vent Ducts.	Effective Length of Core.	Ratio of Pole Arc to Pitch.
						in.	in.	in.	in.	in.	in.	in.	in.			in.	
119	4	117	183	500	471	22½	9½	1.78	.52	.463	.635	4.77	28	None	None	25.2	.73
120	4	42	417	500	442	16	9.42	1.539	.542	.708	.970	1¾	7½	"	"	6.75	.766
121	4	33.3	504	500	442	14.5	3.31	1.45	.245	.154	.245	4.14	8.5	"	"	7.65	.582
122	4	24.2	555	560	453.5	16	4½	1.4	.240	.164	.239	4.35	8	"	"	7.2	.655
123	4	27	640	500	441	11	6.17	1.29	11/16	.445	.724	1.125	9	½ in.	3	7.42	.69

Number of Slots.	Conductors per Slot.	Winding. Number of Circuits.	Winding. Number of Windings.	Winding-Turns in Series between Brushes.	Cycles per Second at Rated Output.	Flux-Megalines.	Number of Teeth Directly Under Pole-Face.	Number of Teeth taken as Transmitting Flux.	Maximum Apparent Tooth Density at Root of Tooth (Kilolines).	Density below Slots.	Total Core Loss.	Weight of Laminations below Slots (Pounds).	Weight of Laminations in Teeth (Pounds).	Total Weight of Laminations (Pounds).	Watts per Pound.	Cycles per Second = C.	Density below Slots = D.	$\frac{CD}{1000}$.	$K\left(\frac{CD}{1000} \times K = \text{Watts per Lb.}\right)$
61	6	2	Single	91	6.1	21.2	11.1	13	140	88	2650	1487	413	1900	1.395	6.1	88	.536	2.61
33	24	2	"	198	13.9	4.02	6.4	7	120	170	1420	117	81	198	7.16	13.9	170	2.36	3.03
93	8	2	"	186	16.8	3.54	13.8	17	177	56	890	212	58	270	3.30	16.8	56	.94	3.51
105	8	2	"	210	18.5	2.92	17	19	130	4.65	800	245	60	305	2.52	18.5	46.5	.86	3.05
29	24	2	"	174	21.4	2.96	5.1	6	148	177	1120	54	45.7	100	11.20	21.4	177	3.78	2.96

tion of coils, in relation to which the frequency of commutation has an important bearing. The curves of Figs. 118 and 124 are plotted from the tabulated results, and will be found useful for the corresponding type of machine.

Suppose, for example, we wish to predetermine the core loss of a multipolar generator having, say, eight poles and running at 240 revolutions per minute. From previous calculations we find it requires 7000 lb. weight of total laminations, including teeth and core body, allowing a full load working density of 76 kilolines per square inch of cross-sectional area of

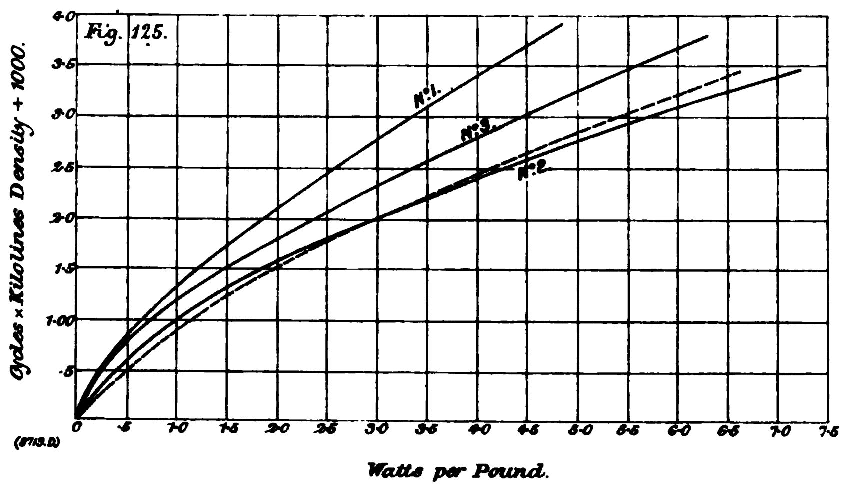


FIG. 125. CORE LOSS OBSERVATIONS BY MESSRS. ESTERLINE AND REID

the core body. Now, eight poles and 240 revolutions per minute correspond to sixteen cycles per second.

$$\frac{\text{Cycles} \times \text{density in kilolines}}{1000} = \frac{16 \times 76}{1000} = 1.22.$$

According to curve, Fig. 118, we obtain 2.1 watts per pound, and as there is a weight of 7000 lb., the total core loss will be 2.1 × 7000 = 14,700 watts.

For the range of periodicity and flux density covered by the above tabulated machines, an average value of 1.7 is obtained for K. Hence the following approximate rule is derived :—

$$\text{Watts per lb.} = \frac{1.7 \times \text{cycles per second} \times \text{kilolines density.}}{1000}$$

The authors have found this method to afford a more reliable guide than any other process, either theoretical or empirical; and it is obviously far more direct than the theoretically more attractive methods set forth in most treatises on dynamo design.

The value of our method has recently been strikingly confirmed by the results of a most elaborate investigation, described in a paper contributed by Messrs. Esterline and Reid to the Transactions of the American Institute of Electrical Engineers, 1903. Messrs. Esterline and Reid's investigations comprised 12,000 observations on variously-proportioned armatures, and the practical results at which they ultimately arrived are given in Fig. 125. It will be seen that the core loss in watts per kilogram is found to be a function of the product of periodicity and core density, the conclusion at which the present writers had arrived several years ago. In Fig. 125 it is stated by Messrs. Esterline and Reid that curve No. 1 may be taken as representative of smooth cores within either solid or laminated poles, curve No. 2 of toothed cores within solid

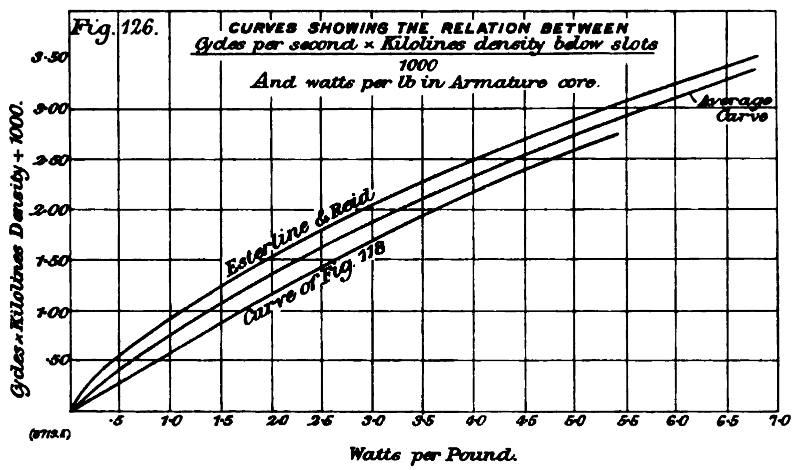


FIG. 126. CORE LOSS CURVES FOR CONTINUOUS-CURRENT GENERATORS

poles, and curve No. 3 of toothed cores within laminated poles. To these curves Messrs. Esterline and Reid have added a broken line curve, which they have obtained from the core-loss tests of a large number of commercial machines, having, in the majority of cases, tooth cores and solid cast poles.

We have re-plotted this last curve in Fig. 126, together with our own curve of Fig. 118. The agreement is so close as to dispel any further doubt as to the best method of procedure in calculating the core losses in practical designing.

In dealing with dynamo calculations generally, due allowance must be made for variations in materials, and slight variations in dimensions and finish incident to ordinary shop methods. This applies more particularly to calculations of iron losses, since in practice it is almost impossible to

make two identically similar cores. We do not suggest, therefore, that in a rigorous examination of results there will not be found considerable variations from the calculated results by the empirical methods suggested. The successful designer must invariably allow for such variations in material and dimensions as occur in reasonably well-regulated practice. Within these limits, the above method has been found to be accurate. Within the limits obtainable in really scientific work, the empirical way of proceeding would not be of any particular value. Dynamo design, however, cannot become a strictly scientific process, until dynamos are built in a laboratory, and not in a commercial workshop.

The question of core loss, as affecting the economy, is not of vital importance in armatures, being of chief interest from the thermal standpoint. But with transformers it is of the utmost importance, as it is the controlling factor in determining the all-day efficiency. Special consideration will be given hereafter to the matter of core loss in transformers. At this point it will be sufficient to state that iron of at least as good quality as that shown in Curve B of Fig. 39, page 37, should be specified and secured. Even with sheets carefully japanned, or separated by paper, the eddy-current loss in transformers will be from one-and-a-half to twice the theoretical value given in the curves of Fig. 40, page 37. This may, perhaps, be explained by supposing the flux not to follow the plane of the sheet, but to sometimes follow a slightly transverse path, thus having a component in a direction very favourable for the setting up of eddy currents in the plane of the sheets. In Figs. 149 and 150, on page 146, will be found curves especially arranged for convenience in determining *transformer* core losses.

In addition to considering the subject of heating from the standpoint of degrees rise of temperature per watt per square inch of radiating surface, it is useful in certain cases to consider it on the basis of rate of generation of heat, expressed in watts per pound of material. Similarly to the manner in which the curves of Figs. 39 and 40, above referred to, give the rate of generation of heat in iron by hysteresis and eddy currents, there are given in Fig. 127 curves showing the rate of generation of heat in copper, due to ohmic resistance. One's conception of the relative magnitudes of these quantities in copper and iron is rendered more definite by a study of the values given in Tables XXXII. and XXXIII.

Table XXXIII. should also be used in calculating iron losses at high densities, as it extends beyond the range of the curves of Figs. 39 and 40.

Smooth-core armatures can be run at higher current densities than iron-clad armatures, owing to the better opportunity for cooling the copper. Likewise with iron-clad armatures, those with a few large coils have to be designed with lower current densities than those in which the winding is subdivided into many smaller coils.

TABLE XXXII.—COPPER

Current Density in Amperes per Square Inch.	Rate of Generation of Heat by Ohmic resistance. Watts per Pound.					
	0 Deg. Cent.	20 Deg. Cent.	40 Deg. Cent.	60 Deg. Cent.	80 Deg. Cent.	100 Deg. Cent.
500	.50	.54	.58	.62	.67	.71
1000	2.00	2.15	2.33	2.48	2.68	2.84
1500	4.40	4.74	5.1	5.5	5.9	6.2
2000	7.9	8.4	9.1	9.1	10.6	11.2
2500	12.3	13.3	14.3	15.3	16.5	17.3
3000	17.7	19.0	20.6	22.8	23.7	25.0

TABLE XXXIII.—SHEET IRON

Flux Density (Kilolines per Square Inch.)	Rate of Generation of Heat by Hysteretic Resistance (and by Ohmic Resistance to the Extent to which Eddy Currents are Present).			
	25 Cycles.	60 Cycles.	100 Cycles.	125 Cycles.
20	.10	.25	.44	.59
40	.27	.75	1.3	1.85
60	.56	1.5	2.8	4.0
80	.92	2.5	4.8	6.7
100	1.4	3.8	7.3	10.5
120	2.0	5.4	10.5	15
140	2.8	7.7	15	22

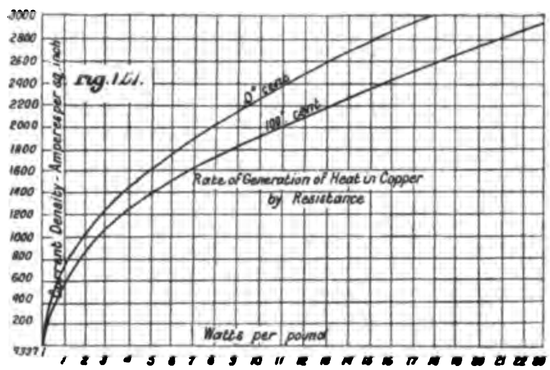
In Table XXXIV. are given some rough figures for the current densities used in various cases :—

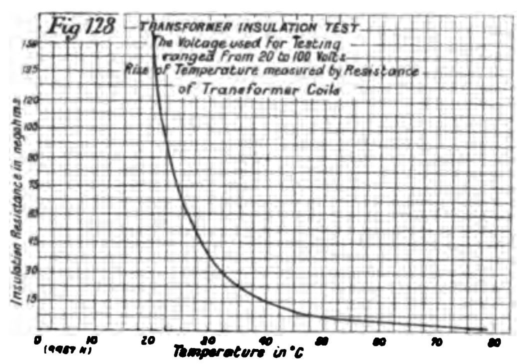
TABLE XXXIV.

	Amperes per Square Inch.
Small high-speed armatures	3500 to 4000
Large " "	2000 " 3000
Small low-speed armatures	2000 " 3000
Large " "	1500 " 2500
Transformers with forced circulation of oil or air ...	800 " 1500
Large transformers immersed in oil or air	500 " 900
Small " " "	500 " 1100

In the case of small transformers the current density could be very much higher without causing excessive temperature rise, but such trans-

formers would have poor regulation. On the other hand, large transformers, when properly designed, have better regulation than is necessary, the current density being limited from thermal considerations. Although many large transformers were until recently so poorly designed that a few hours' run at full load heated them up to above 100 deg. Cent., this was bad practice, as it caused deterioration both of insulation and of iron.[1] A rise of not more than 60 deg. Cent. should be aimed at, even with large transformers.





FIGS. 127 AND 128. HEAT AND INSULATING RESISTANCE CURVES

The curve of Fig. 128 shows that even a rise of 60 deg. Cent. reduces the insulation resistance of a transformer to a small percentage of its resistance when cold. In other words, insulating substances have a very large negative temperature coefficient. In this case, where the insulating material was a composition of mica and cloth, the transformer being immersed in oil with which the insulation was thoroughly impregnated, the average temperature coefficient between 20 deg. Cent. and 80 deg. Cent.

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[1] See pages 34 to 38 for discussion of deterioration of iron at high temperatures.

was -0.8, that is, the insulation resistance increased 80 per cent. per deg. Cent. decrease of temperature. But the ability of this insulating material to withstand the disruptive effects of very high potentials is practically unimpaired. Consequently, it is important to distinguish carefully between the ability to withstand the application of high voltages and the insulation resistance, as measured in megohms. The insulation resistance in megohms returns to its original high value when the transformer is again cold.

Railway Motors

The necessity in this class of apparatus of having high efficiency at light loads (which is the condition under which railway motors operate the greater part of the time), requires that they shall be designed with an efficiency curve which quickly reaches its maximum, and falls off very much at larger loads. As a consequence, a good railway motor cannot be operated for long periods at its full rated drawbar pull, without reaching an excessive and dangerous temperature. The need for compactness also requires running at high temperature under the condition of long-sustained full load. In the section relating to the design of railway motors, this matter is more fully considered.

Constant-Current Arc Dynamos

Arc dynamos are designed to maintain constant current, partly, and sometimes almost entirely, by inherent self-regulation. This requires a large number of turns both on field and armature, and in order to obtain reasonable efficiency, the conductors have to be run at very low-current densities. As a consequence, a properly-designed arc dynamo will run much cooler than would be at all necessary from the thermal standpoint. Such a machine must be, of course, large and expensive for its output.

In apparent contradiction to the above statement stands the fact that almost all arc machines at present in operation run very warm. But this is because almost all arc machines as now in use have such low efficiencies, particularly at anything less than full load, as to render it extremely wasteful to continue them in service. By throwing them all out, and installing well-designed apparatus, the saving in maintenance would quickly cover the expenses incurred by the change. Constant-current dynamos are now rapidly going out of use, arc lighting being more and more extensively done from constant potential circuits.

Constant Potential Dynamos

In constant potential dynamos it should be the aim to have the electromagnetic and thermal limits coincide. Forty or fifty degrees Centigrade, thermometrically determined, rise in temperature during continuous running is generally considered entirely satisfactory, although the requirements for Admiralty and other Government work are usually more rigid. In constant-potential machines the efficiency is so high (especially when compared with the engine efficiency) when the temperature limit is satisfactory, that the efficiency should seldom be a determining factor. Proper thermal and electromagnetic constants should be the limiting considerations.

In dynamos it is customary to quote the efficiency at the temperature reached by the machine at the end of several (generally ten) hours' run; but in the case of transformers, it is generally quoted at 20 deg. Cent. Nothing except prevailing practice justifies these contradictory methods.

Commutator Heating

The heating of the commutator arises from three causes — the mechanical friction of the brushes, the C^2R due to the useful current flowing across the contact resistances, and the heating due to the waste currents caused by short-circuiting of adjacent segments, and by sparking. Copper brushes may, under good conditions, be run up to a density of 200 amperes per square inch of contact surface, and even higher in small machines. Carbon brushes should preferably not be run above 35 amperes per square inch of contact surface, except in small machines, where, with good conditions, somewhat higher densities may be used. The pressure need seldom exceed 2 lb. per square inch of brush-bearing surface, and a pressure of 20 oz. per square inch corresponds to good practice. In the case of railway motors this has to be considerably increased, because of the excessive jarring to which the brushes are subjected.

At a peripheral speed of commutator of 2500 ft. per minute, which corresponds to good practice, the rise of temperature of the commutator will seldom exceed 20 deg. Cent. per watt per square inch of peripheral radiating surface for unventilated commutators; and, with careful design as regards ventilation, this figure may be considerably improved upon. The total rise of temperature should not exceed 50 deg. Cent. for continuous running at full load.

The contact resistance offered by carbon brushes at a pressure of

20 oz. per square inch of bearing surface, and at ordinary current densities and peripheral speeds, may be taken at 0.3 ohms per square inch of contact surface. That is, if there are, for instance, four positive and four negative brushes, each with 1.25 square inches of bearing surfaces, the resistance of the positive brushes will be $\frac{.03}{4 \times 1.25} = .006$ ohms, and this will also be the resistance at the negative brushes; consequently, the total contact resistance will be .012 ohms from positive to negative brushes.

The contact resistance of copper brushes need not exceed .003 ohms per square inch of contact surface, and with good conditions will be less.

In estimating the friction loss, the coefficient of friction at the standard pressure, and with the commutator and brushes in good condition may be taken equal to .3.

To illustrate the application of these constants in estimating the heating of a commutator, the case may be taken of a six-pole 120-kilowatt generator with a 30 in. diameter commutator, whose length, parallel to shaft, is 8 in., and which is furnished at each of its six neutral points with a set of four carbon brushes, each having a bearing surface of 1.5 in. × .75 in. = 1.13 square inches. Consequently, there being twelve positive and twelve negative brushes, the total cross-section of contact for the current is 12 × 1.13 = 13.5 square inches.

The capacity of the machine is 480 amperes at 250 volts; consequently, the current density is 36 amperes per square inch. Taking the contact resistance at .03 ohms per square inch, the total contact resistance amounts to $\frac{.03}{12 \times 1.13} \times 2 = .0045$ ohms from positive to negative terminals. Therefore, the C^2R loss is $480^2 \times .0045 = 1050$ watts. Pressure is adjusted to about $1\frac{1}{4}$ lb. per square inch. Total pressure 1.25 × 13.5 × 2 = 34 pounds. Speed = 300 revolutions per minute. Peripheral speed = 2360 ft. per minute. Therefore, foot-pounds per minute = 2360 × 34 × .3 = 24,000 foot-pounds = .73 horse-power = 545 watts.

C^2R	= 1050
Friction	= 545
Allow for stray losses	= 100
Total commutator loss	= 1695

Radiating surface = 8 × 30 × π = 760 square inches.

Watts per square inch = 1695 ÷ 760 = 2.2.

Figuring the rise at 20 deg. Cent. per watt per square inch, there is obtained :—

$$\text{Total rise temperature} = 2.2 \times 20 = 44 \text{ deg. Cent.}$$

Careful tests fail to show any considerable decrease in resistance of contact on increasing the brush pressure beyond 20 oz. per square inch, nor does it change very greatly for different speeds and current densities ; at least, not enough to be worth taking into account in the necessarily rough approximate calculations. It will, of course, be understood that when brushes or commutator are in poor condition, friction, $C^2 R$ and stray losses, are certain to greatly increase.

Friction Loss

The loss through windage and bearing friction is necessarily very dependent upon the nature of the design and the method of driving. When the armature is directly driven from the engine shaft, and is not provided with an outboard bearing, the loss has to be shared by both engine and dynamo. With belt-driven dynamos a third bearing beyond the pulley is sometimes necessary. The loss due to belt friction is not properly ascribable to the dynamo. If the armature and spider are furnished with internal fans and flues, or other ventilating arrangements, the advantage in cooling thereby gained necessarily involves increased friction loss. In a line of high-speed alternators thus designed, the friction loss ranged from 1 per cent. in the large sizes up to 3 per cent. in the small sizes, the range being from 400 kilowatts down to 60 kilowatts capacity; all the machines were belt-driven, the belt losses, however, were not included. The speeds were from 360 revolutions per minute for the 400 kilowatt, up to 1500 revolutions per minute for the 60 kilowatts.

Some similar continuous-current belt-driven generators, for rather lower speeds, had friction losses ranging from 0.8 per cent. in the 500 kilowatt sizes up to 2 per cent., or rather less, in the 50 kilowatt sizes.

Large direct-coupled slow-speed generators will have considerably less than 1 per cent. friction loss, and such machines for 1000 kilowatts and over should have friction losses well within ½ per cent.

DESIGN OF THE MAGNETIC CIRCUIT

In practice, the solution of magnetic problems is generally largely empirical, on account of the very great difficulty in calculating the magnetic leakage, as well as in determining the precise path which will be followed by the magnetic flux in those parts of the magnetic circuit which are composed of non-magnetic material, such as—in dynamos and motors—the air-gap between the pole-face and the armature surface. In closed circuit transformers no such difficulties arise, and the determination of the reluctance of the magnetic circuit becomes comparatively simple.

Analogies between electric and magnetic circuits are misleading, since a magnetic circuit of iron located in air is similar to an electric circuit of high conductivity immersed in an electric circuit of low conductivity, the stream flow being proportional to the relative conductance of the two circuits. Moreover, in magnetic circuits the resistance varies with the flux in a manner dependent upon the form and materials of the magnetic circuit.

For the purpose of calculation it is assumed that the magnetic flux distributes itself according to the reluctance of the several paths between any two points. The difference of magnetic potential between two points is equal to the sum of the several reluctances between these points, multiplied by the flux density along the line over which the reluctances are taken. The permeability of air being unity, and that of iron being a function of the flux density, it follows that a proportion of leakage flux, or flux external to the core of an electromagnet, increases with the flux density in the core, and with the magnetic force. Practically, the function of a magnetic circuit is to deliver from a primary or magnetising member a definite magnetic flux to a secondary member. Thus, in the case of a dynamo or alternator, the function of the field magnets or primary member is to deliver a certain flux to the armature; in the case of a transformer, that of passing through the secondary coils a certain magnetic

flux. The secondary member reacts upon the primary member, and affects the effective magnetic flux according to the amount of current generated in the secondary member. This reaction acts to change the magnetic flux in the secondary member in two ways: first, by reducing the resultant effective magnetomotive force acting on the magnetic circuit; and, secondly, by affecting the magnetic leakage by altering the differences of magnetic potential and distribution of magnetic forces around the magnetic circuit.

In the case of a generator with brushes set with a forward lead, the reaction is such as to demagnetise the field magnets and increase the leakage.

In the case of a motor with brushes set with a forward lead, the reaction is such as to increase the flux through the armature by added magnetomotive force and diminished leakage.

In the case of an alternating-current generator, the reaction is such as to diminish the flux with lagging armature current, or with leading current to increase the flux.

In the case of a transformer with lagging current, the effect is to diminish the effect of the primary current, and with leading current to increase this effect.

As stated above, however, the leakage in general is affected according to the magnetomotive force between any two points. The effective flux in any magnetic circuit is equal to the resultant magnetomotive force divided by the reluctance of the magnetic circuit. Obviously, then, in the design of a magnetic circuit the effects of these reactions have to be carefully calculated. In the design of the field-magnet circuit of dynamos and alternators, the influence of the armature reaction on the effective magnetomotive force may be taken into consideration in the calculations, by assuming a certain definite maximum armature reaction. These armature reactions will be discussed subsequently. Obviously, the flux density and magnetising force may in all cases vary very widely for a given total flux. Therefore, fulfilling equivalent conditions as to efficiency and heating, there is no fixed ratio between the amount of copper and iron required to produce a certain magnetic flux. The designing of a magnetic circuit may then be said to be a question of producing in the secondary member a given effective magnetic flux, with a given amount of energy expended in the primary magnetic coils, combined with a minimum cost of material and labour; the most economical

result is arrived at by means of a series of trial calculations. The energy wasted in the field magnets should not, in the case of continuous-current machinery, generally exceed 1 or 1½ per cent. of the rated output, the permissible values being dependent mainly upon the size and speed. In all cases there is, of course, the condition that the magnetising coils shall be so proportioned as not to heat beyond a safe limit.

In the case of transformers the condition becomes different. There is a constant loss of energy in the magnetic circuit, due to hysteresis. The amount of energy consumed in the magnetising coils at no load is negligible. At full load it is a considerable fraction of the total loss. Transformers are seldom worked at full load for any length of time; consequently the open-circuit losses should be made consistent with the mean load of the transformer. The general design of the magnetic circuit of an alternating-current transformer may then be said to consist, for a given stated output, in securing a satisfactory "all-day" efficiency and satisfactory thermal conditions for a minimum cost of material and labour, both the iron and copper losses being considered.

In the case of continuous-current dynamos, the armature reaction as a factor in determining the design of the field magnets is of greater importance now than heretofore. Thorough ventilation of the armature has so reduced the heating, that from this standpoint the output of dynamos has been greatly increased. The general introduction of carbon brushes, and a more thorough knowledge of the actions in commutation, has greatly increased the output for good operation from the standpoint of sparking. Thus the magnetomotive force of the armature has naturally become a much greater factor of the magnetomotive force of the field magnets. Taking the magnetomotive force of the armature as the line integral through the armature from brush to brush, there are numerous examples of very good commutating dynamos, in which the magnetomotive force of the armature at full load is equal to that of the field magnets. In several large dynamos designed by Mr. H. F. Parshall, which have now been in use for so long a time that there is no question as to satisfactory operation, the magnetomotive force of the armature at full load was 50 per cent. greater than the magnetomotive force of the field magnets; and the number of turns required in the series coils to maintain constant potential was approximately equal to that in the shunt coils to give the initial magnetisation. It is found in practice that the component of the armature magnetomotive force opposing the field magnets, *i.e.*, the demagnetising component,

is from 18 to 30 per cent. of the total armature magnetomotive force. This corresponds to a lead of the brushes of from 9 to 15 per cent. of the total angular distance between successive neutral points, *i.e.*, to an angular lead of from 16 deg. to 27 deg., the angular span of two magnetic fields (north and south) being taken as 360 deg.

The armature reaction, therefore, in modern practice greatly increases the amount of material required in the field-magnet coils and in the field-magnetic circuit, by increasing the economical length of the magnetic core and coils, which in turn tends to increase the magnetic leakage, and therefore to require greater cross-section of magnetic circuit. As yet, however, practice has not been sufficiently developed to reach the limit beyond which the total cost of the dynamo is increased, by increasing the armature reaction. The field magnet may, therefore, be considered, in general practice, a subservient member. The limit, of course, to the armature reaction is frequently reached in the case of such compound dynamos as are required to give an approximately constant potential over the whole working range.

In the case of alternators, the thermal limit of output has been increased by ventilation, as in commutating machines. By the introduction of a general system of air passages, shorter armatures have become possible, consequently, natural ventilation of the armature has been vastly increased.

The tendency in recent practice has been to limit the output of alternators from the standpoint of inherent regulation, and the thermal limit of output has been generally determined to conform with the conditions laid down as to regulation and inductance. Alternators designed to work over inductive lines for power purposes are very frequently designed with one-half the armature reaction that would be used in the case of lighting machines.

A full discussion of the armature reaction of alternators will be given in a later section. It may be stated here, that in uni-slot single-phase alternators, the value of the reluctance of the magnetic circuit becomes very dependent upon the position of the armature slot with respect to the pole-face; hence the reluctance undergoes a periodic variation of n cycles per revolution of the armature, n being the number of field-poles. The variation is generally of so great an amplitude as to make it important to construct the entire magnetic circuit of laminated iron, otherwise the field frame becomes the

seat of a very substantial loss of energy through eddy currents. Although this loss is less serious in multi-slot single-phase alternators and in polyphase alternators, it should be carefully considered; and it will sometimes be found desirable in such machines to adopt a laminated construction of the entire field frame. Even in continuous-current machines, the loss may sometimes be considerable, being of greater value, the fewer the slots per pole-piece, the wider the slot openings, and the shorter the air gap. But in continuous-current machines there are almost always enough slots to insure the restriction of the magnetic pulsations to the vicinity of the pole-face, and hence it is often the practice to laminate the pole-faces only. The pulsations of the flux throughout the magnetic circuit, due to periodic variations in the reluctance, reach their greatest extent in the inductor type of alternator, and constitute one of the objections to most varieties of this type of alternator.

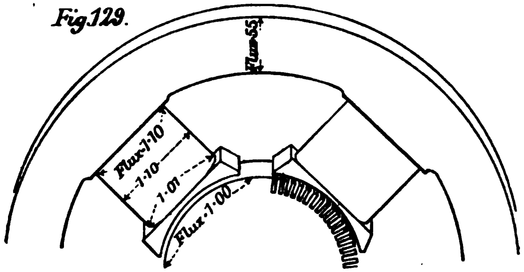
Leakage Factor

The coefficient by which the flux which reaches the armature and becomes linked with the armature turns must be multiplied, in order to derive the total flux generated by the field coils, is known as the "leakage factor," and in most cases is considerably greater than unity. It is evident that the "leakage factor" should increase with the load, since the armature ampere turns serve to raise the magnetic potential between the surfaces of the adjacent pole-faces, and tend to increase the component of flux leaking between adjacent pole-tips and over the surface of the armature teeth above the level of the armature conductors. The diagrams illustrated in Figs. 129 to 134, page 131, give the values of the leakage factors as determined from actual measurements for several cases. It will be noted that in Fig. 132 are given results both with and without current in the armature.

Armature Core Reluctance

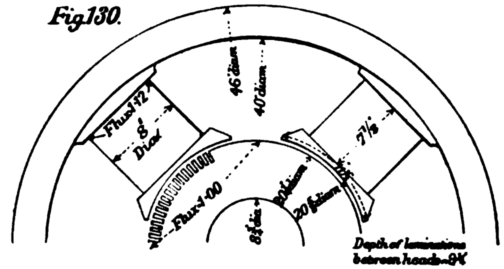
The reluctance of the armature core proper is generally fixed by thermal conditions, which are dependent upon the density and periodicity at which the core is run, the reluctance being chosen as high as is consistent with the permissible core loss.

Fig. 129.



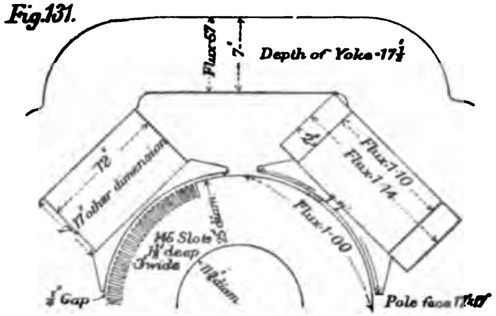
LEAKAGE FACTORS. DIAGRAM I.
100 K.W. Rotary Converter.
In this machine, the leakage factors were only taken at no load. The values were practically independent of the excitation. (4523.A)

Fig. 130.



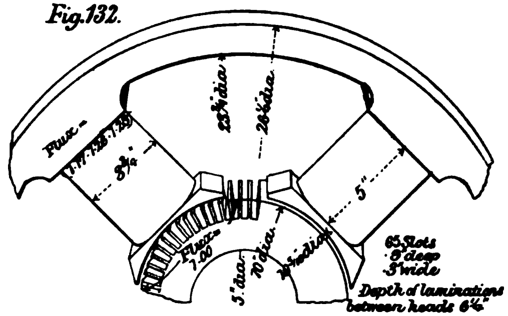
LEAKAGE FACTORS. DIAGRAM 2.
In this machine, the leakage factors were only taken at no load. The values were practically independent of the excitation. (4523.B)

Fig. 131.



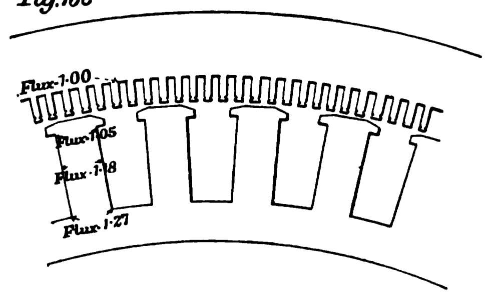
Depth of lamination between heads·16¼" but 10% insulation and four ½" air ducts
LEAKAGE FACTORS. DIAGRAM 3.
The leakage factors were only determined at no load. (4523.C)

Fig. 132.



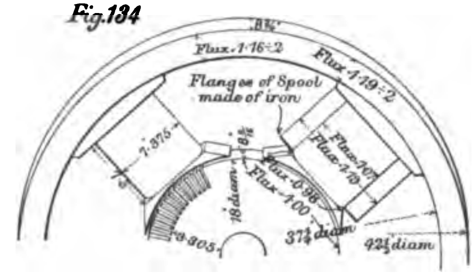
LEAKAGE FACTORS. DIAGRAM 4.
With field exc. of ·33 amps. & no load; leakage factor 1·17
" " " ·72 " " " " 1·26
" " " ·72 " full load " " 1·28
·33 amps exc. required at no load, for rated voltage
·72 " " " full " " " (4523.D)

Fig. 133



LEAKAGE FACTORS. DIAGRAM 5.
Three Phase Dynamo – 750 K.W. output.
In this machine, the leakage factors were only taken at no load. The values were practically independent of the excitation. (4523.E)

Fig. 134



LEAKAGE FACTORS. DIAGRAM 6.
The Values were practically independent of the Excitation. The tests were made with no current in the armature. (4523.F)

FIGS. 129 TO 134. LEAKAGE FACTOR DIAGRAMS

Air Gap Reluctance

The reluctance between the armature core and the faces of the pole-pieces is determined by the space required by the armature conductors, and the necessary mechanical clearance between the armature surface and the pole-faces.[1]

Reluctance of Complete Magnetic Circuit

The reluctance for a given length of magnetic circuit should be such that the combined cost of magnetic iron and magnetising copper is a minimum. The length of the magnetic circuit should be such that, with what may be termed the most economical densities, the cost of the copper and iron is a minimum. By magnetising copper is meant that amount of copper required by the magnetising coils to give, under fixed thermal conditions, that magnetomotive force that will maintain the proper flux

[1] In discussing the sparking limit of output of a smooth-core armature, it has been frequently asserted that the sparking limit of a generator is a function of the depth of the air gap. But the inductance of the armature coils when under commutation is not appreciably diminished by increasing the depth of the air gap, except in machines where the brushes have to be set forward into the near neighbourhood of the pole-tip, which is not necessary in well-designed generators. Therefore, the depth of the air gap has no relation to the magnetic sparking output, except in so far as it may alter the distribution of magnetism in the gap. Beyond a certain limit, increasing the depth of the air gap acts deleteriously on the sparking limit, since the distribution of the magnetic flux in the gap becomes such that the permissible angular range of commutation is very small. In the case of toothed armatures (which are now common practice), the air gap in good practice is made as small as is consistent with mechanical safety. The density in the projections is carried to a very high value, it being generally recognised that the greater the magnetic density at the pole-face, the greater armature reaction is possible without sparking. To satisfy this condition alone, a high density in the projections becomes necessary. It has, however, been pointed out that, with the projection normally worked out, magnetic distortion in the air gap may be made greatly less than in the case of a well-designed smooth-core armature. In the smooth-core machine the distortion in the gap is proportional to the armature reaction; whereas in the case of highly magnetised projections the distortion is greatly less than proportional to the armature reaction. Considered with relation to the inductance of the armature coils, it appears that the inductance of the coils becomes smaller and smaller as the magnetic reluctance in the circuit surrounding the coils becomes increased. All of these conditions may be included broadly by saying that for a given output there is a certain limiting minimum reluctance in the air gap, having regard both to distortion and self-induction. As will be shown later, however, sparkless commutation has to be considered not only in its relation to the inductance of the armature coils and to the strength of the reversing field, but also in respect to the nature of the collecting brushes. Generally speaking, visible sparking, or that external to the brushes, is least injurious to the commutator.

through the armature at full load. The densities should be taken to correspond with the full voltage generated by the armature. The proportions of the magnets should be taken to correspond with the magnetomotive force required at full load.

For a given density the magnet coils should be of a certain length; if too long, the cost of the iron will be excessive; if too short, the cost of the copper will be excessive, since the radiating surface of the coil will be too restricted. The depth of the magnet coil must, in practice, be restricted; otherwise, the temperature of the inner layers will become excessive.[1]

Estimation of Gap Reluctance

The magnetomotive force (expressed in ampere turns) expended in maintaining a flux of D lines per square inch, across an air gap of length L (expressed in inches) is $.313 \times D \times L$. The proof of this is as follows:

$$\text{D lines per sq. in.} = \frac{D}{6.45} \text{ lines per square centimetre.}$$

$$B = \frac{D}{6.45}.$$

For air

$$H = B.$$

$$H = \frac{D}{6.45}.$$

But $H = \dfrac{4\,\pi\,n\,C}{10\,l}$, l being length expressed in centimetres, and $n\,C$ being ampere turns (number of turns $\times$ current).

$$n\,C = \frac{10}{4\,\pi} \times H \times l.$$

$$= \frac{10}{4\,\pi} \times \frac{D}{6.45} \times 2.54\ L.$$

$$= .313 \times D \times L.$$

[1] The increase of temperature of the magnet coils should be determined by the increase in their resistance. Placing the thermometer on the external surface, unless the winding is very shallow, does not give a satisfactory indication. This fails to show whether the inner layers may not be so hot as to increase the resistance of the coil to such an extent that its magnetomotive force at a given voltage is greatly diminished.

Reluctance of Core Projections

The armature projections between the conductors are generally magnetised well towards saturation, so that the determination of the magnetic force required for a given flux across this part of the magnetic circuit is of importance. The following method will be found useful:

The magnetic flux divides between two paths:

1. The iron projections.
2. The slots containing the conductors, and the spaces between the laminations.

The proportion of the flux flowing along each path is proportional to its magnetic conductance. There are several considerations which make the cross-section of the iron path small compared with that of the other paths.

1. In practice, the width of the tooth is generally from 50 to 80 per cent. of the width of the slot.
2. The slot is broader in a direction parallel to the shaft than the iron portion of the lamination, because of the 25 per cent. of the length of the armature frequently taken up by insulation between laminations, and by ventilating ducts.
3. This 25 per cent. of insulation and ducts itself offers a path, which in the following calculation it will be convenient to add to the slot, denoting the total as the air path.

It thus appears that although the iron path is of higher permeability, the air path has sufficiently greater cross-section, so that it takes a considerable portion of the flux; and it will be readily understood that the resultant reluctance of the paths in multiple being considerably less, and the density of the flux being decreased at a point where the permeability increases rapidly with decreasing density, the magnetomotive force necessary for a given flux may be greatly less than that required to send the entire flux through the projections.

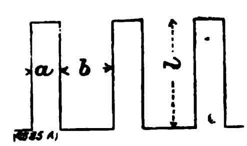


Fig. 135.

Let a = width of tooth.
,, b = ,, slot. (See Fig. 135.)
,, k = breadth between armature heads, of iron part of lamination.
$a\,k$ = cross-section of iron in one tooth.
$\frac{b\,k}{.75}$ = cross-section of slot (because 25 per cent. of the breadth of the armature is taken up by ventilating ducts and insulation between laminations, and the breadth of the slot exceeds that of the iron in the tooth by that amount).

If in any particular design this proportion varies from 25 per cent., new calculations may be made, if the magnitude of the variation is sufficient to warrant it. Moreover, there is 25 per cent. of ventilating ducts and insulation in the breadth of the tooth itself. The cross-section of this will be $.25 \frac{a\,k}{.75} = .33\,a\,k$. It will be convenient to add this to the slots, and denote the total as the air path.

$$\text{Cross-section of air path} = \frac{b\,k}{.75} \times .33\,a\,k = 1.34\,b\,k + .33\,a\,k.$$

This air path, therefore, takes in all paths except the iron lamination.

Let l = depth of tooth and slot.
„ N = lines to be transmitted by the combined tooth and slot, and
μ = permeability of iron and tooth, at true density.

Let the N lines so divide that there shall be

n in iron path, and $N - n$ in air path.

$$\frac{n}{a\,k} = \text{density in iron path.}$$

and

$$\frac{N - n}{1.34\,b\,k + .33\,a\,k} = \text{density in air path.}$$

$$\text{Conductivity of iron path} = \frac{a\,k\,\mu}{l};$$

$$\text{Conductivity of air path} = \frac{1.34\,b\,k + .33\,a\,k}{l}$$

Now, the fluxes n and N—n in iron and air will be directly proportional to the respective conductivities :

$$\frac{n}{N - n} = \frac{\frac{a\,k\,\mu}{l}}{\frac{1.34\,b\,k + .33\,a\,k}{l}} = \frac{\mu\,a}{1.34\,b + .23\,a}$$

$$1.34\,b\,n + .33\,a\,n = a\,\mu\,N - a\,\mu\,n;$$

$$n\,(1.34\,b + .33a + a\,\mu) = a\,\mu\,N;$$

$$\frac{N}{n} = \frac{1.34\,b + .33a + a\,\mu}{a\,\mu}.$$

Let B = true density in iron, and B^1 = density calculated on the assumption that the iron transmits the entire flux. Therefore, the ratio of N (the total lines) to n (those in iron), *i.e*, $\frac{N}{n}$, will equal the ratio of B^1

(the density figured on the assumption that all the lines are in iron), to B (the actual density in iron).

$$\frac{B^1}{B} = \frac{N}{n} = \frac{1.34\,b + .33a + a\,\mu}{a\,\mu}.$$

In Table XXXV. are calculated some values of $\frac{B^1}{B}$ for different values of $\frac{a}{b}$.

TABLE XXXV.

1. $\frac{a}{b} = 1$ (*i.e.*, width tooth = width slot) $\frac{B^1}{B} = \frac{1.67 + \mu}{\mu}$.

2. $\frac{a}{b} = .75$ (" $\frac{3}{4}$ ") $\frac{B^1}{B} = \frac{2.12 + \mu}{\mu}$.

3. $\frac{a}{b} = .50$ (" $\frac{1}{2}$ ") $\frac{B^1}{B} = \frac{3.00 + \mu}{\mu}$.

The next step in this process requires reference to the iron curves of Fig. 136. From these curves Tables XXXVI. and XXXVII. are derived:

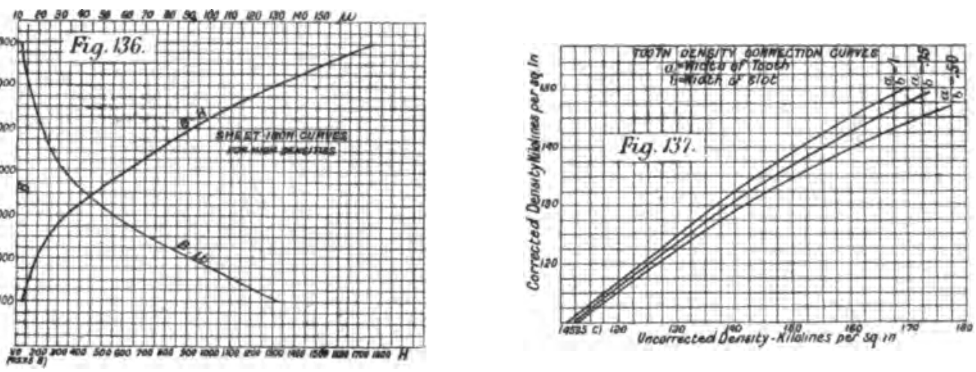
TABLE XXXVI.

Corrected Iron Densities.	—	Densities Figured on Assumption that Iron Transmits Entire Flux.		
B.	μ	$B^1\left(\frac{a}{b} = 1.\right)$	$B^1\left(\frac{a}{b} = .75\right)$	$B^1\left(\frac{a}{b} = .50\right)$
17,000	133	17,200	17,300	17,400
18,000	92	18,400	18,500	18,600
19,000	56	19,500	19,800	20,000
20,000	33	21,000	21,300	21,800
21,000	23	22,500	23,000	23,700
22,000	17	24,200	24,700	26,000
23,000	13	26,000	26,800	28,300

TABLE XXXVII.—DENSITIES IN INCHES

Corrected Iron Densities.	Densities Figured on Assumption that Iron Transmits Entire Flux.		
Kilolines per Square Inch.	$\frac{a}{b} = 1.$	$\frac{a}{b} = .75$	$\frac{a}{b} = .50$
110	111	112	113
116	119	120	121
123	127	128	129
129	136	138	141
136	145	149	153
142	156	160	168
149	168	173	183

In the curves of Fig. 137, the values of the densities in the Tables have been transposed into kilolines density per square inch, and are thus available for use in dynamo calculations, where the process simply consists in figuring the iron density as if the iron transmitted the entire



FIGS. 136 AND 137. SHEET IRON AND DENSITY CURVES

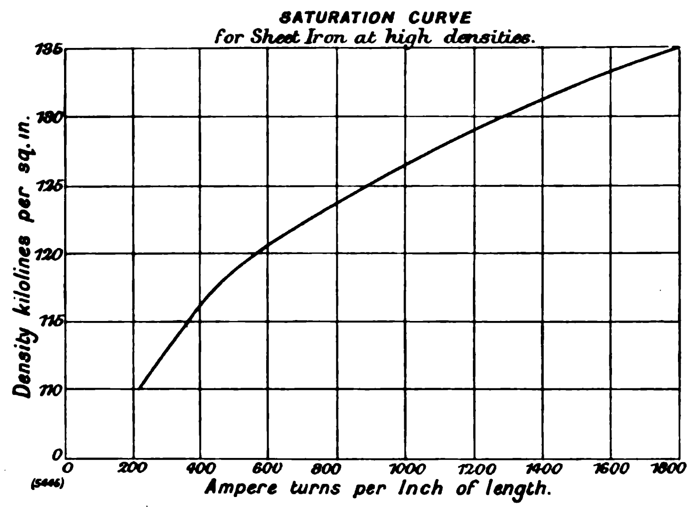


FIG. 138. SATURATION CURVE

flux, and obtaining from the curves a corrected value for use in figuring the magnetomotive force.[1] The number of teeth to be taken as transmitting

[1] This method was devised by one of the writers in 1892, and the results were at that time incorporated in the set of curves here produced in Fig. 137. These curves are identical with those published ten years later, in 1902, in Fig. 7, at page 32 of Dr. Thompson's "Design of Dynamos"; and at page 147 of Vol. I. of the Seventh Edition of the same author's "Dynamo-Electric Machinery." They had already been published in 1900, in Fig. 127, on page 126 of the First Edition of "Electric Generators." The assumptions are crude; nevertheless the now fairly general use of this method twelve years after it was first employed, and notwithstanding the appearance of numerous alternative methods in the meantime, justifies the belief that it is probably one of the most useful methods for approximate practical calculations, where economy in time is an object.

the flux has to be determined by judgment, and is influenced by the length of the gap. Generally, increasing by one the number lying directly under the pole-face gives good results for machines with very small air gaps, while two or three extra teeth should be added for larger gaps.

Fig. 138 gives for high densities the magnetomotive force in ampere-turns per inch of length, in dependence upon the density in kilolines per square inch.

Calculation for Magnetic Circuit of Dynamo

The following example of a very simple case may be of interest, as giving some idea of the general method of handling such problems :

A certain ironclad dynamo has an air-gap density of 40 kilolines (per square inch), the density in the magnet core is 90 kilolines, and in the magnet yoke 80 kilolines. The frame is of cast steel. The tooth density is 110 kilolines, and the armature density is 50 kilolines.

			in.
Length of gap	... ...	=	.25
"	magnet core (as related to the magnetic circuit)	=	10
"	yoke (corresponding to one spool)	=	6
"	tooth	=	1.5
"	armature (corresponding to one spool)	=	4

Required number of ampere-turns per spool at no load :

Ampere-turns for gap = .313 × 40,000 × .25	=	3130
Ampere-turns for magnet core (from curve A of Fig. 17, page 23) = 47 × 10	=	470
Ampere-turns for yoke = 29 × 6	=	170
Ampere-turns for teeth (from curve B of Fig. 25) = 150 × 1.5	=	230
Ampere-turns for armature core = 6 × 4	=	20
Total		4020

Therefore ampere-turns per pole-piece at no load = 4020.

It thus appears that, for practical purposes, it is much more direct to proceed as in the above example than to go through a laborious calculation of the total reluctance of the magnetic circuit, incidentally bringing in the permeability and other factors, as described in many text-books.

FIELD WINDING FORMULA

In making field winding calculations, the following formula is of great service:

$$\text{Lb.} = \frac{31 \times \left(\frac{\text{Ampere-feet}}{1000}\right)^2}{\text{watts}}$$

in which

Lb. = Pounds of copper per spool.
Ampere-feet = Ampere-turns × mean length of one turn, expressed in feet.
Watts = watts consumed in the spool at 20 deg. Cent.

This formula is derived as follows:

Resistance between opposite faces of a cubic inch of commercial copper at 20 deg. Cent. = .00000068 ohms.

If length in inches = L, and cross-section in square inches = S, then

$$R = \frac{.00000068\ L}{S}$$

$$S\ L = \frac{.00000068\ L^2}{R}$$

Let l = mean length of one turn in inches.
t = number of turns.
$l\ t$ = L.

$$S\ L = \frac{.00000068\ l^2\ t^2}{R}$$

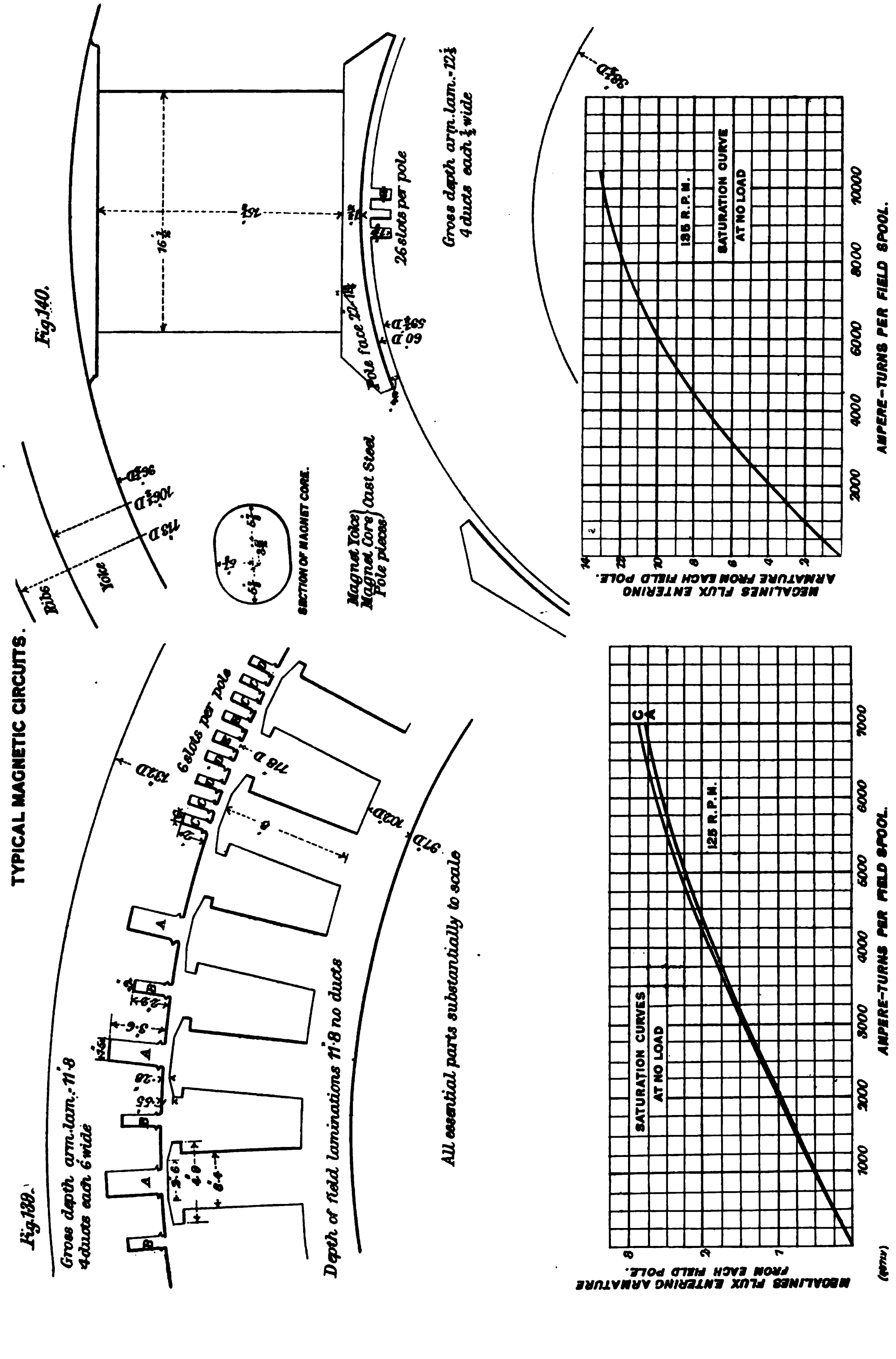
$$= \frac{.00000068\ C^2\ l^2\ t^2}{C^2\ R}.$$

$\frac{C\ l\ t}{12}$ = ampere-feet (ampere-turns × mean length of one turn in feet.)
$C\ l\ t$ = 12 × ampere feet.
$C^2\ l^2\ t^2$ = 144 (ampere-feet)^2.
$C^2\ R$ = watts

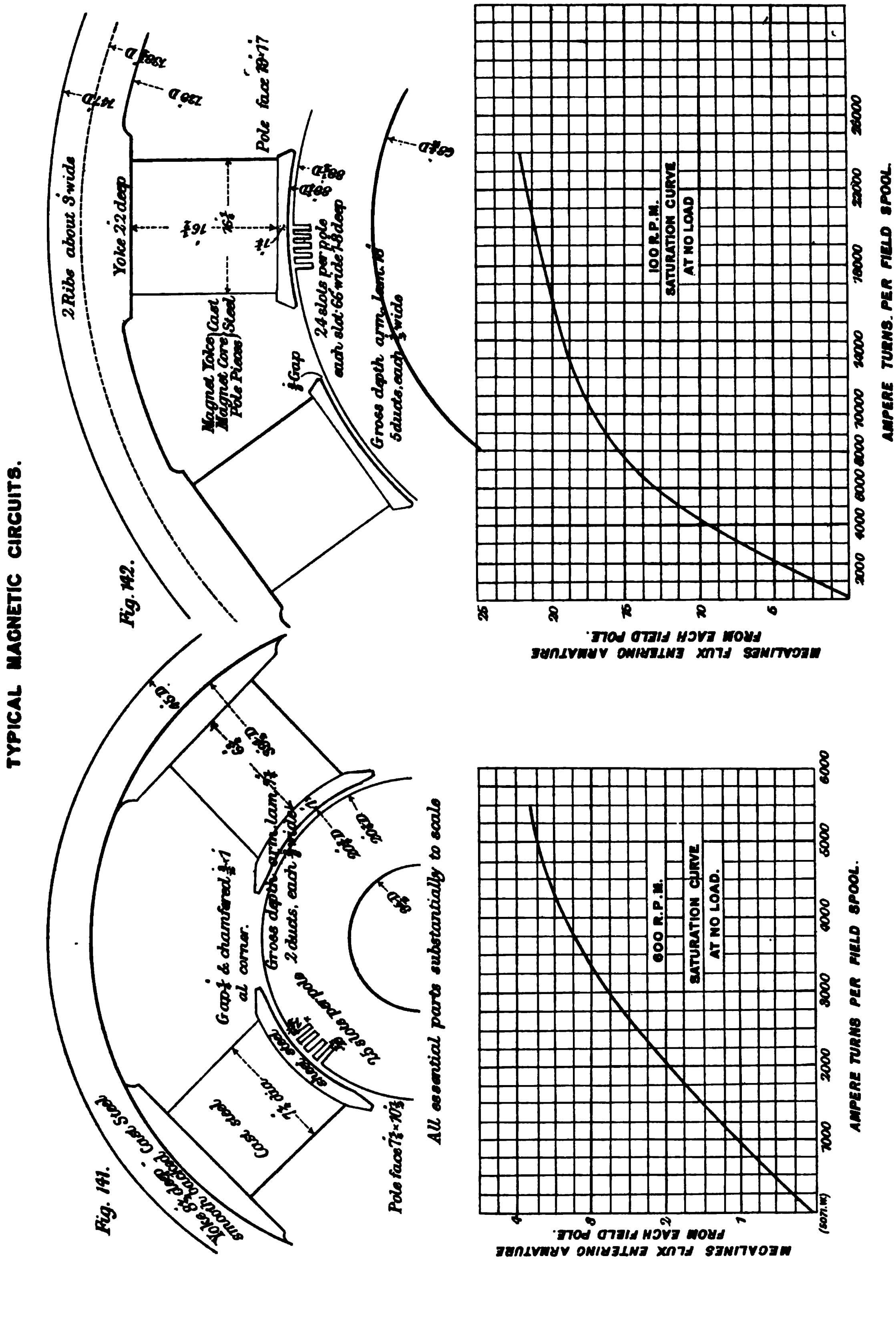
$$S\ L = \frac{.68 \times 144 \times \left(\frac{\text{ampere-feet}}{1000}\right)^2}{\text{watts}}$$

$$\text{Lb.} = .32\ S\ L = \frac{.32 \times .68 \times 144 \times \left(\frac{\text{ampere-feet}}{1000}\right)}{\text{watts}}$$

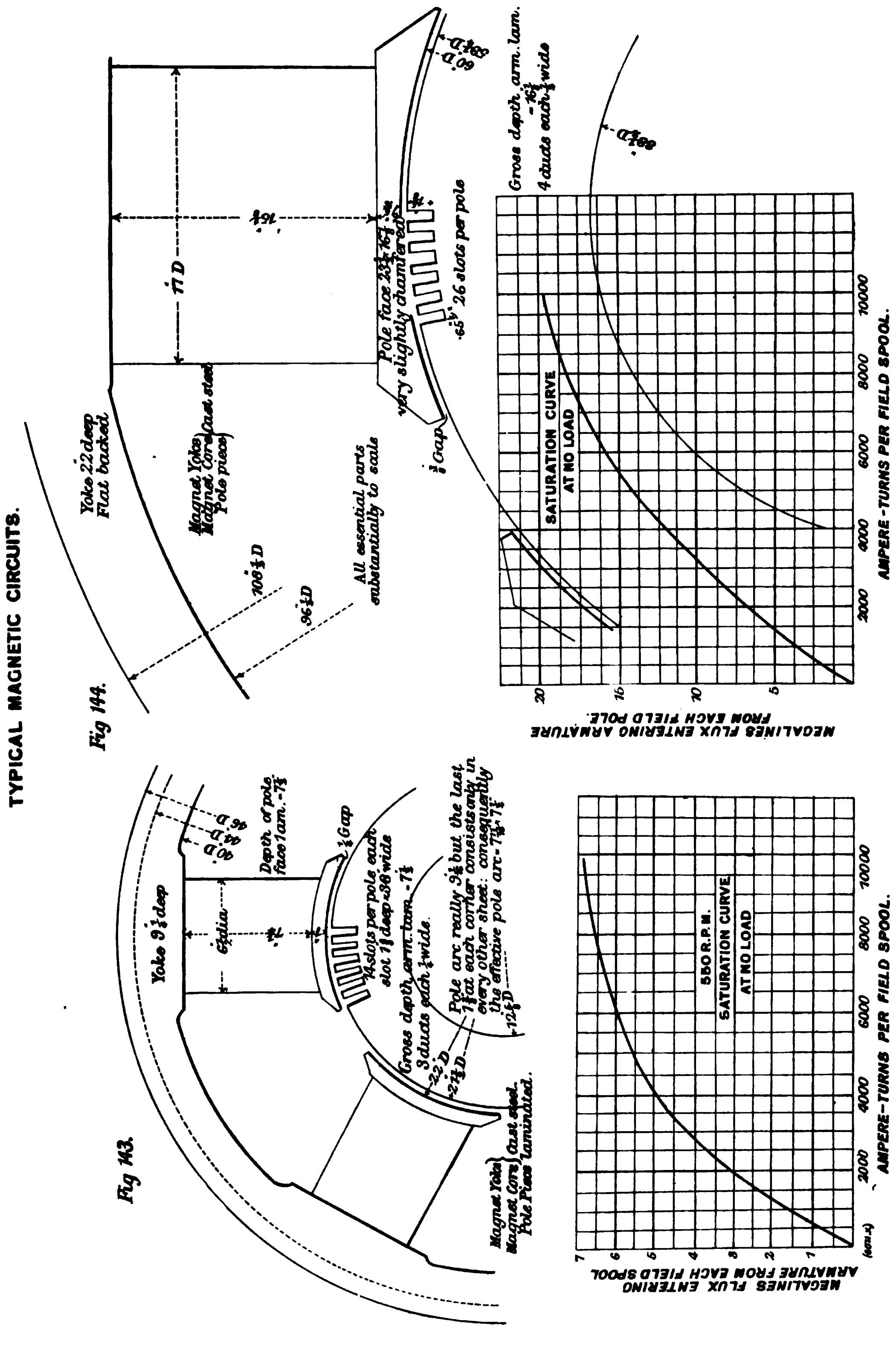
$$\text{Lb.} = \frac{31 \times \left(\frac{\text{ampere-feet}}{1000}\right)^2}{\text{watts}}$$



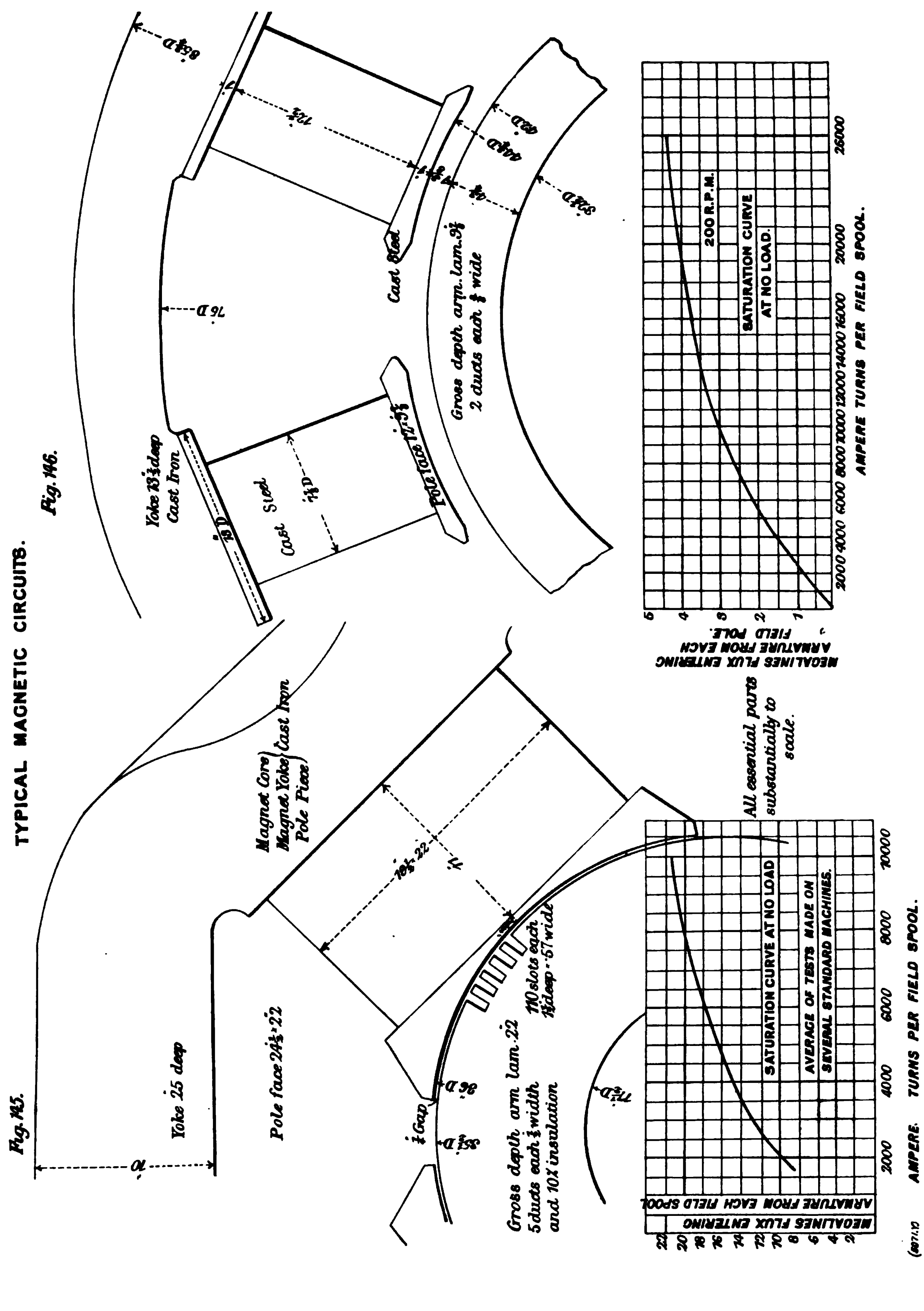
FIGS. 139 AND 140. TYPICAL MAGNETIC CIRCUITS AND THEIR SATURATION CURVES



Figs. 141 and 142. Typical Magnetic Circuits and their Saturation Curves



FIGS. 143 AND 144. TYPICAL MAGNETIC CIRCUITS AND THEIR SATURATION CURVES



FIGS. 145 AND 146. TYPICAL MAGNETIC CIRCUITS AND THEIR SATURATION CURVES

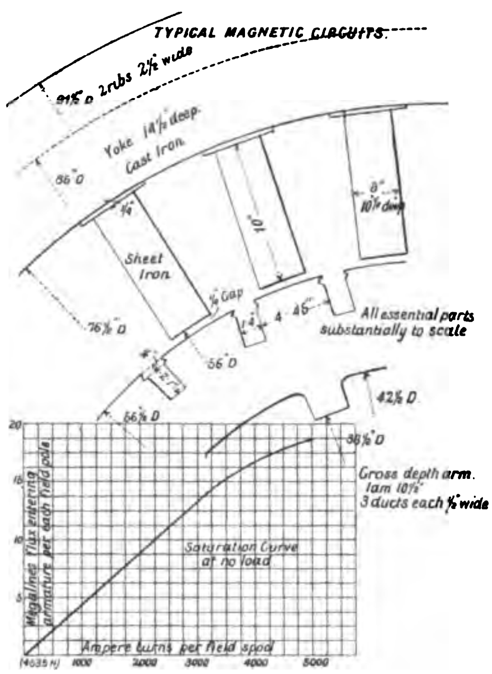
Application to Calculation of a Spool Winding for a Shunt-Wound Dynamo

Thus, suppose the case of a machine for which it had been determined that 5,000 ampere-turns per spool would be required. Assume that the mean length of one turn is 4.0 ft. Then

$$\left(\frac{\text{ampere-feet}}{1000}\right)^2 = \left(\frac{5000 \times 4}{1000}\right)^2 = 400.$$

Fig. 147

Fig. 148



Figs. 147 and 148. Typical Magnetic Circuit and Saturation Curve

The radiating surface of the spool may be supposed to have been 600 square inches. After due consideration of the opportunities for ventilation, it may be assumed to have been decided to permit .40 watts per square inch of radiating surface at 20 deg. Cent. (it, of course, increasing to a higher value as the machine warms up).

$$\therefore \text{watts} = 600 \times .40 = 240 \text{ per spool.}$$

$$\therefore \text{lb. copper per spool} = \frac{31 \times 400}{240} = 52 \text{ lb.}$$

This illustrates the application of the formula, but it will be of interest to proceed further and determine the winding to be used.

A six-pole machine will be taken, designed for separate excitation from a 250 volt exciter. In order to have room for adjustment, as well as

to allow for probable lack of agreement between the calculated and actual values, it is desirable to have but 220 volts at the winding terminals under normal conditions of operation. This is 220/6 = 36.7 volts per spool.

The conditions as regards ventilation indicate a rise of 30 deg. Cent. in the temperature of the spool winding under the conditions of operation. Then the watts per spool are:

$$1.17 \times 240 = 280 \text{ watts at 50 deg. Cent.}$$

$$\text{Amperes} = \frac{280}{36.7} = 7.6$$

$$\text{Turns per spool} = \frac{5000}{7.6} = 655$$

And as the mean length of one turn is 4.0 ft., the total length of winding is:

$$655 \times 4 = 2620 \text{ ft.}$$

$$\text{Pounds per 1000 ft.} = \frac{52}{2.62} = 19.8$$

From the Table of properties of commercial copper wire, it will be found that No. 12 B. and S. has 19.8 lb. per 1000 ft., and is, therefore, the proper size. Generally, the desired value for the pounds per 1000 ft. does not come out very nearly like that of any standard size of wire. In such a case the winding may be made up of two different sizes of wire, one smaller and the other larger than the desired size. Generally, however, it is sufficiently exact to take the nearest standard size of wire.

Suppose the space inside the spool flanges to have been 10 in. long, then, after insulating, $9\frac{1}{2}$ in. would probably be available for winding. From the Table of properties of commercial copper wire it will be found that double cotton-covered No. 12 B. and S. has a diameter of .091 in. Therefore it should have 9.5/.091 = 105 turns per layer. The plan is to take only 100 turns per layer, so as to have a margin.

$$\text{Number of layers} = 655/100 = 6.6 \text{ layers.}$$

Therefore, the winding will consist of 6.6 layers of 100 turns each, of D.C.C. No. 12 B. and S., and will require 220 volts at its terminals when warm, it carrying 7.6 amperes.

Calculations relating to the compounding coils of machines will be given later, after the theory of armature reaction has been developed.

It is now proposed to give experimentally determined no-load saturation curves for several different types of machines, together with sufficient of the leading dimensions of the machines to enable the results to be profitably studied and compared.

In the case of Fig. 139, page 140, two machines were tested, the fields being the same, but one armature having slots as shown at A and B, and the other as shown at C, D, and E. The armature coils used in the tests were those in slots A and C respectively. For figuring the flux in the case of A, the "form factor" was taken as 1.25. For C, the "form factor" was taken as 1.11. In the case of a winding at B, the results would probably have corresponded to an appreciably different "form factor" from that used for A. In the tests the coils contained in the slots B were not employed.

Fig. 149.

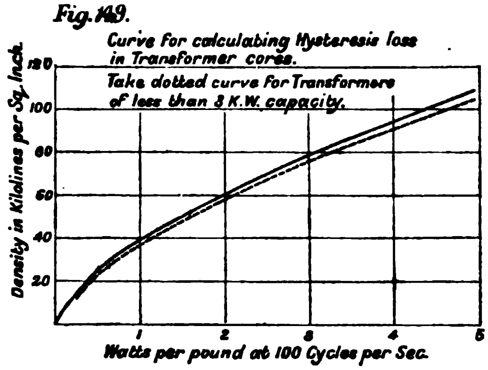
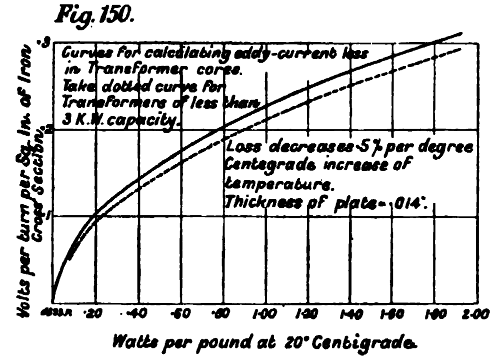


Fig. 150.



FIGS. 149 AND 150. CURVES FOR CALCULATING HYSTERESIS AND EDDY-CURRENT LOSSES IN TRANSFORMER CORES

The saturation curves A and C exhibit the results and show the total reluctance of the magnetic circuit to be substantially the same for the two cases. In Figs. 140 to 148, inclusive, pages 140 to 144, eight other examples are given, the necessary data accompanying the figures.

MAGNETIC CIRCUIT OF THE TRANSFORMER

The following example will give a general idea of the considerations involved in the calculation of the magnetic circuit of a transformer, and will illustrate the use of B-H and hysteresis and eddy-current curves:

Ten-kilowatt Transformer.—The magnetic circuit is shown in the sketch (Fig. 151, page 148). Primary voltage = 2000 volts. Secondary voltage = 100 volts. Primary turns = 2340, periodicity 80 cycles per second. E = 4 F.T.N.M. $\times 10^{-8}$. Assume that the transformer is to be used on a circuit having a sine wave of electromotive force. The "form factor" of a sine wave is 1.11; hence

$$F = 1.11$$
$$2000 = 4 \times 1.11 \times 2340\ 80 \times M \times 10^{-8}$$
$$M = 240{,}000 \text{ lines} = .24 \text{ megalines.}$$

Effective cross-section of magnetic circuit = $3.13 \times 3.13 \times .90$[1] = 8.8 square inches.

Density = 27.3 kilolines per square inch.

First calculate the magnetising component of the leakage current. From curve B of Fig. 25 (page 28), we find that at a density of 27.3 kilolines there is required about three ampere-turns of magnetomotive force per inch length of magnetic circuit.

Mean length of magnetic circuit = 59.5 in.

$\therefore$ Require magnetomotive force of $59.5 \times 3 = 179$ ampere-turns.

There are 2340 turns.

$$\therefore \text{ Require a maximum current of } \frac{179}{2340} = .077 \text{ amperes.}$$

$$\therefore \text{ R.M.S. current} = \frac{.077}{\sqrt{2}} = .054 \text{ amperes.}$$

Next estimate the core loss component of the leakage current. Weight of sheet iron = $59.5 \times 8.8 \times .282 = 148$ lb. At 80 cycles and 27.3 kilolines, Fig. 149 shows that there will be a hysteresis loss of $.6 \times .48 = .8$ watts per pound.

Volts per turn per square inch of iron cross-section = $\dfrac{2000}{2340 \times 8.8}$ = .097. From Fig. 150 the eddy current loss is found to be .21 watts per pound.

Consequently, the hysteresis and eddy current loss will be .48 + .21 = .69 watts per pound. Total iron loss = $148 \times .69 = 102$ watts. Core loss component of leakage current = $102 \div 2000 = .051$ R.M.S. amperes.

---

[1] Ninety per cent. of the total depth of laminations is iron, the remaining 10 per cent. being japan varnish or paper for insulating the laminations from each other.

Resultant leakage current $= \sqrt{.054^2 + .051^2} = .074$ amperes. Full load current $= \frac{10,000}{2,000}$ 5.0 amperes.

Consequently the resultant leakage current = 1.4 per cent. of the full-load current. Core loss = 1.02 per cent. of the full-load rated output.

Example.—Find the core loss and the leakage current for the same transformer with the same winding when running on a 2,200 volt, 60 cycles circuit.

Magnetic Circuit of the Induction Motor

In Fig. 152 is represented the magnetic structure of a six-pole three-phase induction motor. The primary winding is located in the external

Fig. 151.

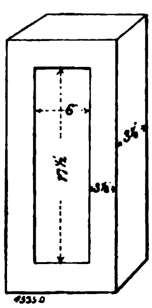
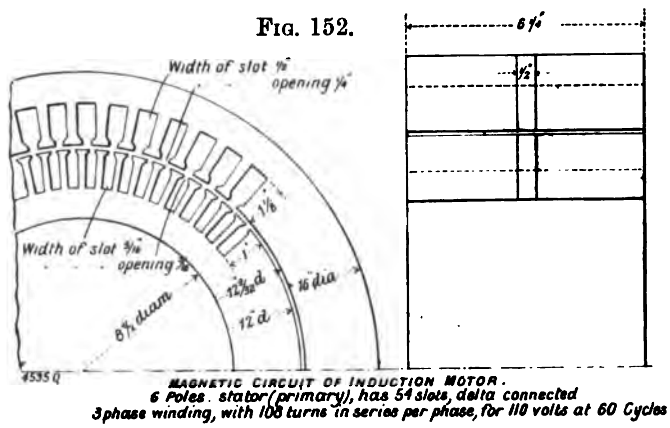


Fig. 152.



Figs. 151 and 152. Magnetic Circuit of a Transformer of an Induction Motor

stator, which has 54 slots. There are 12 conductors per slot, consequently $12 \times 54 = 648$ total face conductors, 324 turns, and 108 turns in series per phase. The motor is for 100 volts, and 60 cycles, and its primary windings are Δ connected. When run from a sine wave circuit, we have

$$110 = 4 \times 1.11 \times 108 \times 60 \times M \times 10^{-8}$$
$$M = .38 \text{ megalines.}$$

Before proceeding to the calculations directly concerned in the determination of the magnetising current for the magnetic circuit of this induction motor, it will be necessary to study the relations between magnetomotive force and flux distribution in this type of magnetic circuit and winding.

In Fig. 153 a portion of the gap face of the primary is developed along a straight line, and the slots occupied by the three windings are lettered A, B, and C. The relative magnitudes of the currents in the three windings at the instant under consideration are given numerically immediately under the letters, and the relative directions of these currents are indicated in the customary manner by points and crosses. The instant chosen is that at which the current in phase A is at its maximum, denoted by 1, the currents in B and C then having the value .5.

The curve plotted immediately above this diagram shows the distribution of magnetic flux in the gap, at this instant, on the assumption that the gap density is at each point directly proportional to the sum total of the magnetomotive forces at that point. Thus the magnetic line which, in closing upon itself, may be conceived to cross the gap at the points

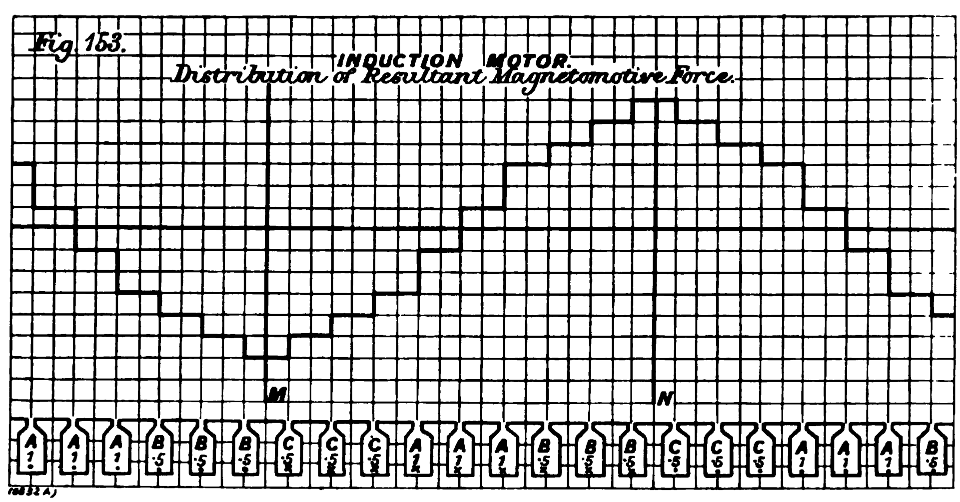


FIG. 153. CURVE OF DISTRIBUTION OF M. M. F. IN INDUCTION MOTORS

M and N, is linked with the maximum ampere turns. Taking the instantaneous current in conductors of phase A as 1, and in phases B and C as .5, and for the moment considering there to be but one conductor per slot, the total linkage of ampere turns with the line $m\ n$ is $3 \times 1 + 6 \times .5 = 6$, and the maximum ordinate is plotted at this point with the value 6.

In the same way the other ordinates are plotted. From this curve it appears that the resultant of the magnetomotive forces of the three phases at the points M and N is twice the maximum magnetomotive force of one phase alone. This is a general property of such a three-phase winding.

Moreover, an analysis of the curve shows the maximum ordinate to be approximately 1.7 times as great as the average ordinate. But this is only in this particular case. With different numbers of slots per pole-piece, this value would vary, and, owing partly to the increased reluctance in the high density teeth, the curve would tend to be smoothed out and become less peaked.

The above considerations are sufficient, as they enable us to determine the maximum values of magnetomotive force and flux, and it is from such values that the maximum magnetising current is derived. But it will be of interest to refer also to Fig. 154, in which are represented the conditions one-twelfth of a complete cycle (30 deg.) later, when the current in phase B

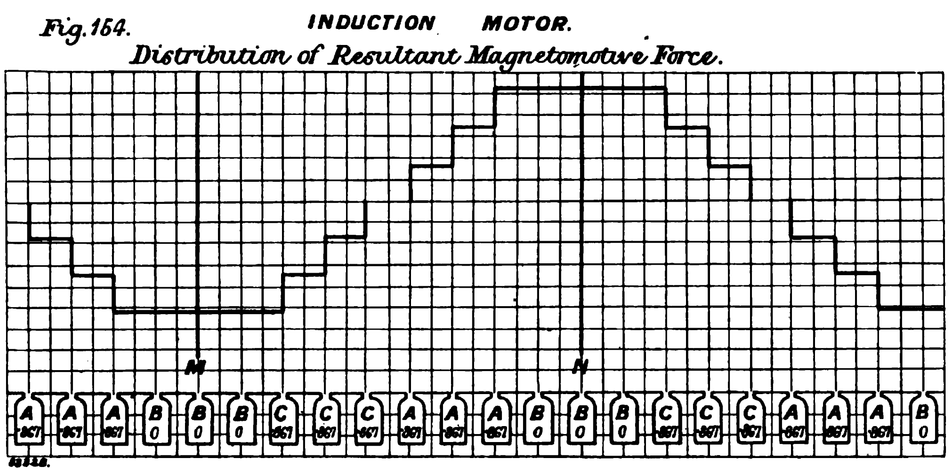


FIG. 154. CURVE OF DISTRIBUTION OF M. M. F. IN INDUCTION MOTORS

has become zero, the current in phases A and C having become .867. Figs. 153 and 154 represent the limiting values between which the resultant magnetomotive force fluctuates as the magnetic field proceeds in its rotatory course about the magnetic structure. Various experimenters have shown this small variation in intensity to be, in practice, practically eliminated. An examination of the diagrams, Figs. 153 and 154, shows that the maximum ordinates are 6 and 5.2 respectively, which corresponds to the theoretical ratio of

$$\frac{\sqrt{3}}{2} : 1 = 1 : 1.16.$$

From Fig. 152 the following cross-sections of the magnet circuit per pole-piece at different positions are obtained :

	Sq. in.
A. Cross-section of air gap per pole-piece at face of stator, *i.e.*, surface area of exposed iron of projections	21
B. Ditto for rotor face	21
C. Cross-section at narrowest part of projections in stator	10
D. Cross-section at narrowest part of projections in rotor	8
E. Cross-section of stator laminations above slots	10
F. Cross-section of rotor laminations above slots	8

FLUX DENSITY

	Average.		Maximum.
A.	18 kilolines	...	30.7 kilolines
B.	18 „	...	30.7 „
C.	38 „	...	64.8 „
D.	48 „	...	82 „
E.	—	...	38 „
F.	—	...	48 „

The depth of the air gap is $\frac{3}{64}$ in. (.047 in.), and the ampere-turns for the air gap amount to

$$.313 \times 30{,}700 \times .047 = 450.$$

For the iron there will be required about 8 ampere-turns per inch of length of the magnetic circuit, which, through the teeth at maximum density, is about 9 in.

$$\text{Ampere-turns for iron} = 8 \times 9 = 72$$
$$\text{Total ampere-turns per pole-piece} = 450 + 72 = 522.$$

Magnetomotive force of the three phases is equal to twice the maximum ampere-turns per pole-piece per phase. There are 18 turns per pole-piece per phase, therefore, letting C = R. M. S. amperes per phase, we have

$$1.41 \times C \times 18 \times 2 = 552.$$

$$C = \frac{552}{1.41 \times 18 \times 2} = 10.9 \text{ amperes} = \text{magnetising current per phase.}$$

Taking the core loss at 300 watts, the friction at 150 volts, and the C^2 R loss running light, at 50 watts, gives a total power, running light, of 500 watts, or 167 watts per phase. Energy component of leakage current per phase $= \frac{167}{110} = 1.5$ amperes.

Resultant leakage current per phase $= \sqrt{10.9^2 + 1.5^2} = 11$ amperes. Ditto per line leading to motor $11 \times \sqrt{3} = 19$ amperes.

Letting power factor, running light, equal P, we have

$$P \times 11 \times 110 = 168$$
$$P = .14.$$

EXAMPLES

The following examples relate to matters dealt with in the foregoing sections:

1. A three-phase generator has 24 poles, 36 slots, 20 conductors per slot, Y connection. Volts between collector rings at no load and 500 revolutions per minute = 3500. What is the flux from each pole-piece into the armature, assuming the curve of electromotive force to be a sine wave? (For type of winding, see Fig. 82, page 78.)

2. A continuous-current dynamo has a two-circuit single winding (drum). Its output is 100 kilowatts at 550 volts. The current density in the armature conductors is 1200 amperes per square inch. It has 668 face conductors. Mean length of one armature turn is 75 in.

What is the cross-section of the armature conductors?

What is the resistance of the armature from positive to negative brushes at 60 deg. Cent.?

The dynamo has six poles. If the speed is 200 revolutions per minute, what is the magnetic flux entering the armature from each pole-piece?

3. A six-pole continuous-current generator with a two-circuit, single winding, gives 600 volts with a certain field excitation and speed. There are 560 face conductors, arranged two per slot in 280 slots. If this winding is tapped off at two points, equi-distant with reference to the winding, what would be the alternating-current voltage at two collector rings connected to these points?

Assume the pole arc to be 60 per cent. of the polar pitch.

4. 100-kilowatt dynamo, 250 volts, 4 poles; 500 revolutions per minute; armature wound with a two-circuit, triple-winding; 402 face conductors arranged in 201 slots. Therefore $\frac{402}{2} = 201$ total turns. $\frac{201}{6} = 33.5$ turns in series between brushes. $\frac{500 \times 2}{60} = 16.7$ cycles per second.

$$250 = 4 \times 33.5 \times 16.7 \times 10^{-8}.$$

$$\therefore M = 11.2 \text{ megalines. Take leakage factor} = 1.20.$$

Flux in magnet cores = $11.2 \times 1.20 = 13.5$ megs. Magnet cores of cast steel, and run at density of 95 kilolines per square inch, therefore cross-section $= \frac{13,500,000}{95,000} = 142$ square inches. Circular cross-section. Diameter = 13.5 in.

Length of armature core parallel to shaft = 16 in., of which 12 in. is solid iron, the remainder being occupied by ventilating ducts and the space lost by the japanning of the iron sheets. Diameter of armature = 30 in. Length of air gap = $\frac{1}{4}$ in. Length of magnet cores = 12 in. Length of magnetic circuit in yoke = about 24 in. per pole-piece. Yoke of cast iron and run at density of 35 kilolines. Tooth density = 120 kilolines. Core density = 70 kilolines. Therefore, depth of iron under teeth = $\frac{11{,}200{,}000}{2 \times 70{,}000 \times 12} = 6.7$ in. Length of magnetic circuit in armature = 10 in. per pole-piece. Pole arc measured along the arc = 17.5 in. Cross-section of pole-face = 16 in. × 17.5 in. = 280 square inches.

$$\text{Pole-face density} = \frac{11{,}200{,}000}{280} = 40 \text{ kilolines.}$$

Ampere-turns per pole-piece for yoke...	= 24 × 60	= 1440
Ampere-turns per pole-piece for magnetic core	= 12 × 50	= 600
Ampere-turns per pole-piece for teeth...	= 1.5 × 350	= 525
Ampere-turns per pole-piece for armature core	= 10 × 12	= 120
Ampere-turns per pole-piece for air gap	= .25 × 40,000 × .313	= 3130
Total ampere-turns per pole-piece at no load and 250 volts		= 5815

CONSTANT POTENTIAL, CONTINUOUS-CURRENT DYNAMOS

The problems peculiar to the design of the continuous-current dynamo are those relating to commutation. The design of the magnetic circuit, and considerations relating to the thermal limit of output, to efficiency and to regulation, although matters of importance in obtaining a satisfactory result, are nevertheless secondary to the question of commutation; and they will consequently be considered incidentally to the treatment of the design from the commutating standpoint.

Under the general class of constant potential dynamos are included not only dynamos designed to maintain constant potential at their terminals for all values of the current output, but also those to maintain constant potential at some distant point or points, in which latter case the voltage at the generator terminals must increase with the current output, to compensate for the loss of potential in the transmission system.

In the commutating dynamo, great improvement has been made in the last few years in the matter of sparkless collection of the commutated current; in consequence of which, the commutator undergoes very little deterioration; and it is customary to require the dynamo to deliver, without harmful sparking, any load up to, and considerably in excess of, its rated output, with constant position of the brushes. This has been made necessary by the conditions of service under which many of these machines must operate; and the performance of such machines is in marked contrast to that of the dynamos of but a few years ago, in which the necessity of shifting the brushes forward in proportion to the load was looked upon as a matter of course. The change has been brought about by the better understanding of the occurrences during commutation, and to the gradual acquisition of data from which satisfactory constants have been deduced. One of the most important factors has been the very general introduction of high-resistance brushes, the use of copper brushes now generally being resorted to only for special purposes.

Radial bearing carbon brushes are now used very extensively, and

although they were at first considered to be applicable only to high potential machines, where the quantity of current to be collected would not require too large and expensive a commutator, their use has been extended to low-voltage machines of fairly large output, the advantages being considered to justify the increased cost of the commutator. Various types of brushes have been developed, intermediate in resistance between carbon and copper, and different grades of carbon brushes, from high-resistance grades with fine grain for high potential machines, to grades of coarser grain and lower resistance for low potential machines. A corresponding development has been taking place in the design of brush-holding devices. In the construction of the commutator, care is now taken to insulate the segments by mica, which shall wear at as near as possible the same rate as the copper segments; and the construction of the commutator has now reached a stage where uneven bars and other sources of trouble of earlier days now no longer give concern. Of less importance, owing to the greatly increased durability of the modern commutator, are the modes of construction whereby sectors of the commutator may be renewed without disturbance to the remainder of the commutator. This is a method much employed in large commutators. Amongst the examples of modern dynamos which follow the discussion of matters of design, will be found illustrations of various types of commutator construction.

The advance thus briefly summed up, in the mechanical design and in the careful choice of material for brushes, brush holders, and commutators, has been in no small measure responsible for the improvement in commutating dynamos; and, when accompanied by correct electro-magnetic proportions, has enabled manufacturers to dispense, in machines for normal conditions, with the many ingenious but complicated windings and devices arranged to modify sparking by the use of various electro-magnetic principles requiring auxiliary windings, subsidiary poles, and other additions. Some of these non-sparking devices accomplish their purpose very effectively; but, notwithstanding the care and ingenuity displayed in their application, it does not appear likely that it will be commercially profitable to resort to them, except in the case of dynamos to be driven by steam turbines and of motors for very high speeds, since the careful application of ordinary methods appears to have already brought the constant potential commutating dynamo to that stage of development where the thermal limit of output of armature and field is reached below that output where harmful sparking occurs. Further improvement rendering it permissible to use more

highly-conducting brushes without encountering sparking, would of course result in a saving in the cost of the commutator, and from some source or other such improvement may appear. But as the saving can apparently only be effected at the commutator, it will not be sufficient in amount not to be more than offset by the increased cost of resorting to any of the auxiliary windings and devices yet proposed.

Armature Reaction

The study of the problems relating to sparking resolves itself down principally to the study of the reaction of the armature, which will now be considered and illustrated with relation to its influence upon the proportioning of commutating dynamos, the choice of windings, and, finally, by descriptions of some modern dynamos.

When discussing the formulæ for electromotive force and the design of the magnetic circuit, it was pointed out that considerations relating to armature reaction make it necessary to modify the conclusions arrived at when these phenomena are left out of consideration. The formula for the electromotive force $E = K\ T\ N\ M\ 10^{-8}$, has already been given. Additional conditions are, however, imposed by the necessity of giving T, the turns, add M, the flux, such relative values as to fulfil the conditions necessary to obtain sparkless collection of the current, and satisfactory regulation of the voltage, with varying load.

The requirements for commutating or reversing the current in the coil that is to be transferred from one side of the brush to the other, consist in so placing the brushes that when the coil reaches the position of short-circuit under the brushes, it shall have just arrived in a magnetic field of the direction and intensity necessary to reverse the current it has just been carrying, and to build up the reversed current to a strength equal to that of the current in the circuit of which it is about to become a part. In such a case, there will be no spark when the coil passes out from the position of short circuit under the brush. Now it is plain that, as the current delivered from the machine is increased, it will require a stronger field to reverse in the coil this stronger current. But, unfortunately, the presence of this stronger current in the turns on the armature, so magnetises the armature as to distort the magnetic field into a position in advance of the position of the brushes, and also to weaken the magnetic flux. The brushes must therefore be shifted still further, whereupon the demagnetising effect of

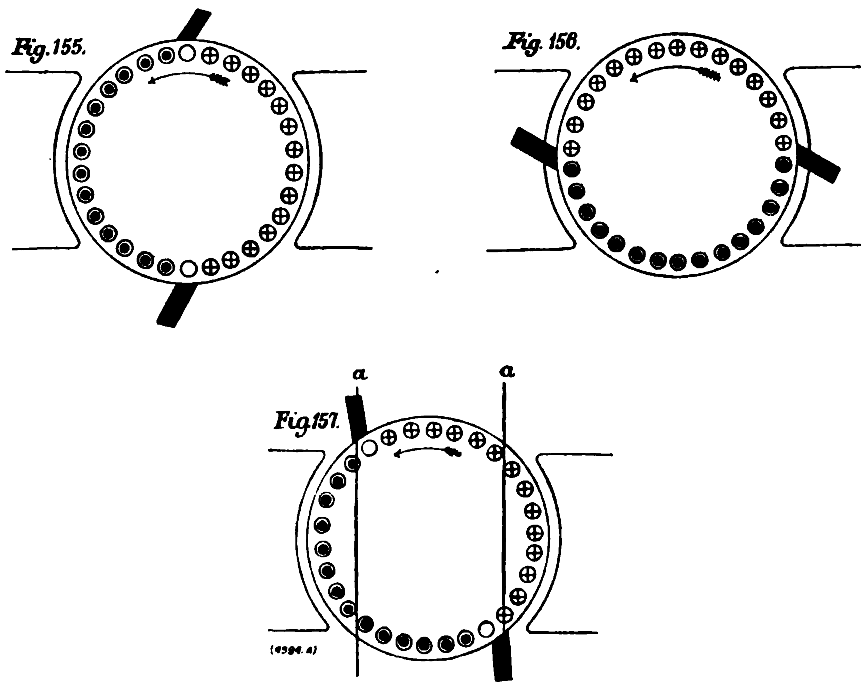
the armature is again intensified. Finally, a current output will be reached at which sparkless collection of the current will be impossible at any position, there being nowhere—by the time the brushes are moved to it—any place with sufficient strength of field to reverse and build up to an equal negative value the strong armature current, during the time the coil is passing under the brush.

These distorting and demagnetising effects of the armature current are made quite plain by the diagrams given in Figs. 155 to 157, page 158, in which the winding is divided into demagnetising and distorting belts of conductors.

In Fig. 155 the brushes are in the neutral zone, and the current is distributed in the two sets of conductors, so as to tend to set up a flux at right angles to that which, the armature carrying no current, would be set up by the field. The resultant flux will be distorted toward the forward pole tip, considered with reference to the direction of rotation. Therefore, at this position of the brushes, the electromagnetic effect of the armature is purely distortional. Similarly, if, as in Fig. 156, the brushes were moved forward through 90 deg. until they occupied positions opposite the middle of the pole faces, and if in this position, current were sent through the brushes into the armature (the armature with this position of the brushes being incapable of generating current), the electromagnetic effect of the armature would be purely demagnetising, there being no component tending to distort the field; and in any intermediate position of the brushes, such, for instance, as that shown in Fig. 157, the electromagnetic effect of the armature current may be resolved into two components, one demagnetising, and due to the ampere turns lying in the zone defined by two lines (a a) drawn perpendicularly to the direction of the magnetomotive force of the impressed field, and passing through the forward position of the two brushes, and the other component due to the ampere turns lying outside of the zone, and purely distortional in its tendency. Fig. 157, of course, represents roughly the conditions occurring in actual practice, Figs. 155 and 156 being the limiting cases, shown for explanatory purposes.

In this connection, it will be of interest to give the results of a test on armature reaction. A small four-pole iron-clad generator of 17-kilowatt capacity, at 250 volts, with a four-circuit single-winding, was tested with regard to the distribution of the magnetic flux in the gap. For this purpose the gap was divided up into a number of sections,

from each of which successively an exploring coil was withdrawn. The coil was in circuit with a resistance box, and with the moveable coil of a Weston voltmeter. From the deflections and the total resistances of the circuit, the intensity of the flux at different portions of the gap was determined. These determinations were made with the armature at rest. As shown on the curves of Fig. 158, readings were taken, first with the field excited, but with no current in the armature (curve A), and then with full-load current



FIGS. 155 TO 157. DIAGRAMS OF DISTORTING AND DEMAGNETISING EFFECTS OF ARMATURE CURRENT

in the armature, and for various positions of the brushes. With the brushes at the neutral point (curve B), the distortion is at a maximum, but there is no demagnetisation. It would have been expected that the distortional crowding of the lines would have so increased the maximum density as to slightly diminish the total flux at the excitation used, this excitation being maintained at a constant value throughout the test. The integration of curves A and B, however, gives equal areas, consequently there was in this case no diminution of the total flux.

But when the brushes are shifted over to the middle of the pole face

(curve E), the demagnetisation becomes very marked, as may be seen not only by the shape of the curve, but by its total area which is proportional to the total flux, but there is no longer any distortion. This last curve (curve E), representing the flux distribution corresponding to the position of the brushes at the middle of the pole face, should have been symmetrical, its lack of symmetry possibly being due to variation in the depth of the gap.

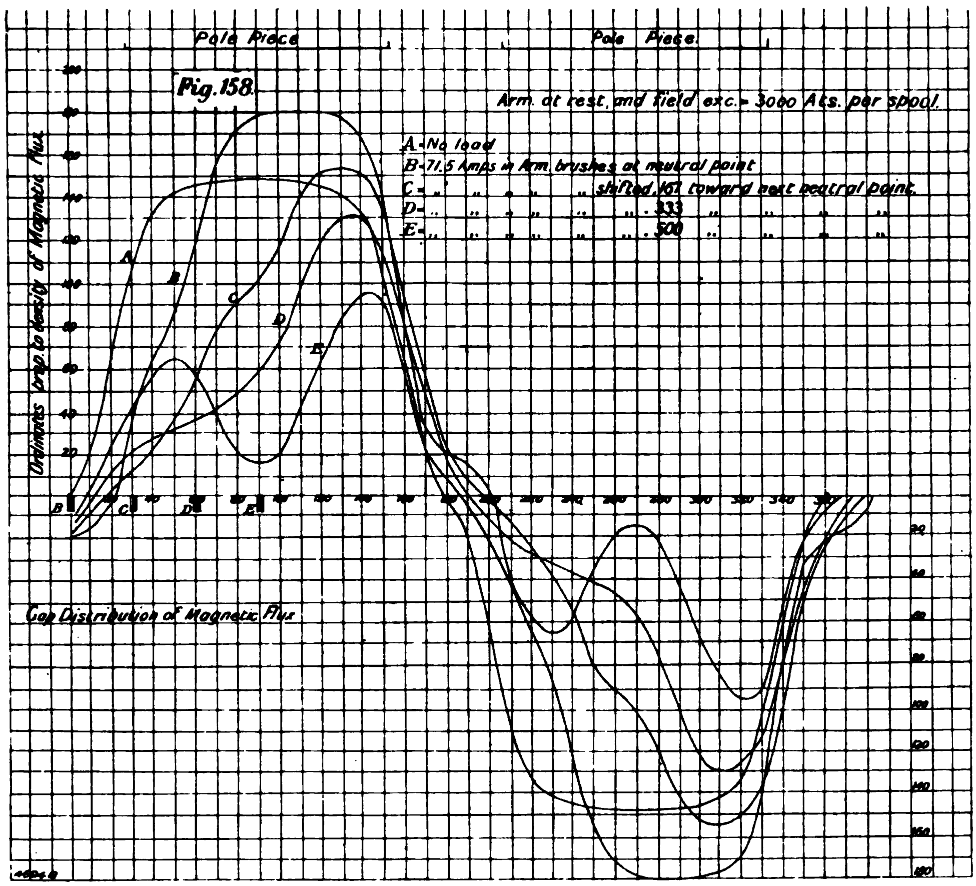


FIG. 158. CURVES OF GAP DISTRIBUTION OF MAGNETIC FLUX WITH VARIOUS LEADS OF BRUSHES

Dr. Hopkinson[1] has made experiments upon the distribution of the magnetic flux in the air gap of two Siemens Brothers' bipolar dynamos, the results of which correspond very closely with his calculations with reference to the influence of armature reaction. A

[1] "Original Papers on Dynamo Machinery and Allied Subjects." By John Hopkinson. Whittaker and Co., London, 1893.

similar analysis of the curves of Fig. 158 also confirms the theory of armature reaction. The machine experimented upon had a four-circuit drum-winding, with 79 coils of six turns each, in 79 slots in the periphery. There were, therefore, $\frac{79 \times 6}{4} = 119$ turns per pole piece on the armature. The armature current being 71.5 amperes, there were $71.5 \div 4 = 18$ amperes per turn; consequently, $119 \times 18 = 2140$ ampere turns per pole piece on the armature. The area of the curves, which are proportional to the flux entering the armature, are as follows:

A.	49 square centimetres	=	100 per cent.
B.	49 ,, ,,	=	100 ,,
C.	36 ,, ,,	=	74 ,,
D.	27 ,, ,,	=	55 ,,
E.	20 ,, ,,	=	41 ,,

For curves A and B, the demagnetising component is zero, there being, however, in the case of B, maximum distortion, which would have been expected to so increase the maximum gap density as to cut down the total flux due to the 3000 field ampere turns per pole piece. This was not, however, the case.

In curves C, D, and E, the demagnetising component of the armature strength rose to $\frac{1}{3} \times 2140 = 710$ at C, $\frac{2}{3} \times 2140 = 1420$ at D, and to the full strength of 2140 ampere turns at E. These results can be tabulated as follows:

TABLE XXXVIII

1	2	3	4	5	6	7
Designation of Curve.	Percentage that Flux Entering Armature is of Total Flux at no Load. Determined from Area of Curves of Fig. 147.	Field Ampere Turns, Maintained Constant throughout the Tests.	Armature Ampere Turns, Maintained Constant throughout the Tests.	Demagnetising Component of Armature Ampere Turns determined from Position of Brushes. See Diagrams of Figs. 144, 145, and 146.	Resultant Ampere Turns, Determined from Columns 3 and 5.	Percentage that Resultant Ampere Turns are of no Load Ampere Turns, Determined from Column 6.
A	100	3000	0	0	3000	100
B	100	3000	2140	0	3000	100
C	74	3000	2140	710	2290	76
D	55	3000	2140	1420	1580	53
E	41	3000	2140	2140	860	29

The large percentage of flux in curve E (41 per cent.), as compared with the small percentage of resultant ampere turns (29 per cent.), is

explained by the fact that with the brush at the middle of the pole face, as was the case in curve E, many of the armature turns are so situated in space as not to be linked with the entire flux, and consequently cannot be so effective in demagnetisation. In other words, the armature turns are uniformly distributed, instead of being concentrated in a coil placed so as to fully oppose the field coils. The extent of this non-effectiveness is proportionate to the pole arc, but with the positions of the brushes which would occur in practice, the demagnetising component of the armature ampere turns would be fully effective.

It will be observed that for curves A, B, C and D, the proportion of flux to resultant ampere turns is very close.

The above experiments show that the effect of the distorting component of the total ampere-turns, in decreasing the total effective flux, is in this case negligible. The authors have, however, made further tests, and have found that this is only the case in machines with a low saturation of the teeth, and generally also a deep air-gap.

To clear up this subject, a study of armature demagnetisation was carried out by the authors on the 550-kilowatt, 550-volt, ten-pole, slow-speed (90 revolutions per minute) generator, described in detail further on (see Index). During all the tests, which will here be described, the brushes were set with a lead of eight segments, and the series spools were disconnected. The terminal voltage, the armature current, and the field magnetomotive force, were measured, and are set forth in the first three columns of Table XXXIX. The values in Column IV. are obtained by subtracting the values in Column III. for zero armature current, from the following values in Column III. with increasing armature current.

The influence of the distorting ampere-turns may be obtained by subtracting from the total armature reaction the components due to ohmic drop and to armature demagnetisation.

The armature winding of this machine consists of ten parallel circuits of 90 turns per circuit (*i.e.*, per pole). As there is one turn per segment, the number of segments per pole is also 90. A displacement of the brushes by eight segments corresponds therefore to $2 \times 8 = 16$ demagnetising turns per pole, or to $\frac{16 \times C}{10}$ demagnetising ampere-turns per pole, where C is the total armature current. These values are given in Column V, Table XXXIX. The ohmic drop per ampere in the armature and brush

TABLE XXXIX

Brush Lead = 8 Segments.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
Terminal Voltage, Volts.	Armature Current, Amperes.	Field Magnetomotive Force, Ampere Turns per Pole.	Field Magnetomotive Force Required to Overcome Armature Interference (M).	Demagnetising, Ampere Turns per Pole (G).	Ohmic Drop in Volts.	Ampere Turns for Overcoming Ohmic Drop, from Saturation Curve (H).	G + H.	Field Ampere Turns for Overcoming Distortion, F = M − (G + H).	Total Distortioning Ampere Turns, 7.4 × Armature Current (D).	F in Percentage of Total Distortioning Ampere Turns (D).
400	0	4,650	0	0	0	0	0	0	0	—
400	300	5,350	700	480	4.5	85	565	135	2220	6.1
400	500	6,100	1450	800	7.3	142	942	508	3700	13.8
400	690	6,800	2150	1110	10.3	195	1305	845	5100	16.5
450	0	5,600	0	0	0	0	0	0	0	0
450	335	6,680	1080	530	5	100	630	450	2480	17.0
450	570	7,250	1650	915	8.5	170	1085	565	4220	13.4
450	785	8,750	3150	1250	11.7	235	1485	1665	5800	29.9
500	0	6,630	0	0	0	0	0	0	0	—
500	380	7,660	1030	610	5.7	140	750	280	2810	10.0
500	650	9,050	2420	1040	9.7	240	1280	1140	4810	23.7
500	870	10,300	3670	1400	13.0	325	1725	1945	6440	30.2
550	0	7,980	0	0	0	0	0	0	0	—
550	420	9,340	1320	670	6.3	190	860	460	3110	14.7

contact is about 0.015 volts, therefore the ohmic drop = 0.015 C volts, and is given in Column VI.

The ampere-turns necessary to overcome the ohmic drop (Column VII.) may be estimated from the saturation curve given in Fig. 159, page 164. The ampere-turns, F, remaining after deducting these two components, G and H, from the total armature demagnetisation, are given in Column IX., and represent the magnetomotive force required for overcoming distortion. The total distorting ampere-turns, D, on the armature per pole are equal to 9.0 C − 1.6 C = 7.4 C. These values are set forth in Column X. The percentages which, F, the field ampere-turns required for overcoming distortion (values in Column IX.), bear to, D, the total distorting ampere-turns on the armature (values in Column X.), are set forth in Column XI.

This percentage varies somewhat erratically, as must be expected in rough tests on so large a machine; but with the exception of one out of

TABLE XL.—CALCULATION OF FIELD AMPERE-TURNS REQUIRED TO OVERCOME ARMATURE INTERFERENCE. 550 KILOWATTS, 10 POLE, 90 R.P.M. RAILWAY GENERATOR

Terminal Voltage.	Total Armature Flux per Pole.	Apparent Density at Roots of Teeth (Square Inches).	Corrected Density at Roots of Teeth (Square Inches).	Ampere Turns per Inch for Teeth.	Length of Teeth in Inches.	Ampere Turns for Teeth (A).	Pole Face Density (Square Inches).	Length of Air-Gap in Inches.	Ampere Turns for Air-Gap (B).	S = A + B.	Armature Current.	Armature Current per Pole.	Total Distorting Ampere Turns per Pole (D).	$\frac{D}{S}$.	$\frac{F}{D}$ from Fig. 149.	F.	Demagnetising Ampere Turns per Pole (G).	Ampere Turns to Overcome Ohmic Drop (H).	Ampere Turns at No-Load, same Terminal Voltage (K).	Total Ampere Turns (F + G + H + K).	Total Ampere Turns (F + G + H + K) Observed.	Error in Percentage of Observed A.T.
400	15	92,000	92,000	38	2	80	34,500	0.375	4040	4120	300	30	2220	0.54	0.075	168	480	85	4650	5,381	5,350	+0.6
400	15.2	93,500	93,500	38	,,	80	34,800	,,	4080	4160	500	50	3700	0.89	0.15	556	800	142	4650	6,148	6,100	+0.8
400	15.4	95,000	95,000	38	,,	80	35,300	,,	4140	4220	690	69	5100	1.21	0.23	1170	1110	195	4650	7,125	6,800	+4.8
450	16.9	104,000	104,000	66	,,	130	38,700	,,	4560	4690	335	33.5	2480	0.53	0.08	198	530	100	5600	6,428	6,680	−3.7
450	17.1	105,000	105,000	76	,,	150	39,200	,,	4600	4750	570	57.0	4220	0.89	0.16	675	915	170	5600	7,360	7,250	+1.5
450	17.2	106,000	106,000	81	,,	160	39,300	,,	4630	4790	785	78.5	5800	1.21	0.24	1400	1250	235	5600	8,485	8,750	−3.0
500	18.9	116,000	113,500	178	,,	360	43,200	,,	5080	5440	380	38	2810	0.52	0.11	310	610	140	6630	7,690	7,660	+0.4
500	19.0	117,000	114,000	203	,,	410	43,500	,,	5150	5560	650	65	4810	0.87	0.18	865	1040	240	6630	8,775	9,050	−3.0
500	19.1	117,500	115,000	229	,,	460	43,900	,,	5170	5630	870	87	6440	1.14	0.27	1730	1400	325	6630	10,085	10,300	−2.1
550	21.0	129,000	125,000	610	,,	1200	48,000	,,	5700	6900	420	42	3110	0.45	0.125	390	670	190	7980	9,230	9,300	−0.8

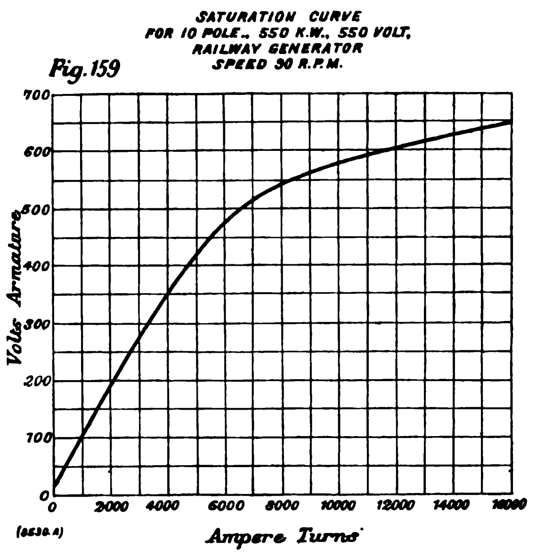
the ten total observations, the values show that it is a function of the total distortion and of the saturation of the teeth and air-gap.

Let D = total distorting ampere-turns per pole.

Let F = field ampere-turns for overcoming D, the total distorting ampere-turns per pole.

Then the ratio $\frac{F}{D}$ may be obtained from Fig. 160, in which it is plotted as a function of the ratio $\frac{D}{S}$, where

S = ampere-turns required for air gap and teeth.



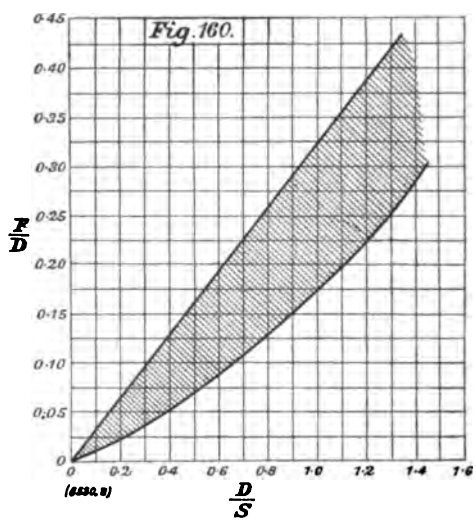


FIG. 159 SATURATION CURVE

FIG. 160. CURVES FOR CALCULATING THE INFLUENCE OF DISTORTING AMPERE-TURNS

The higher the tooth saturation the more one will approach the upper limit of the shaded area in Fig. 160, and *vice versâ*.

It will now be of interest to work from this data as a basis for illustrating the application of this method of determining the total field excitation required for a given load and voltage. This is carried out in Table XL., on the preceding page, for the 10-pole 550-kilowatt machine, on which the experimental data was obtained.

APPLICATION OF THESE CONSIDERATIONS TO THE PROPORTIONING OF DYNAMOS

If it were not for the effects due to the electromagnetic reaction of the armature, the proportioning of dynamos would resolve itself

into a determination of those values of T and M in the formula $E = KTNM \times 10^{-8}$, which would, with a minimum cost of material, give the desired current and voltage; suitable cross-section of copper and iron being chosen, to secure immunity from excessive heating. Thus suppose the problem should arise, of the best design for a 500-volt 100-kilowatt generator, to run at 600 revolutions per minute. The current output is 200 amperes. Let us try a two-pole drum winding with 10 face conductors. Then $T = 5$; $N = 10$; $500 = 4 \times 5 \times 10 \times M \times 10^{-8}$, $M = 250{,}000{,}000$ lines. The armature iron could not properly be run at more than 100,000 lines per square inch. Therefore, the cross-section of the armature = 2500 square inches at least. It thus appears that the armature would have to be 50 in. in diameter and 50 in. long, or else some other equally extreme dimensions. The field turns would be of great length, and as the air-gap density would be very high, there would be need for very many field ampere turns. Without carrying the calculations any farther, it is apparent that, as regards cost of materials alone, the machine would be poorly designed.

On the other hand, suppose the armature had 2000 face conductors. Then $T = 1000$; $500 = 4 \times 1000 \times 10 \times M \times 10^{-8}$, $\therefore M = 1{,}250{,}000$ lines. Necessary cross-section = 12.5 square inches as far as regards transmitting the flux. Therefore, the magnet cores would be 4 in. in diameter. But to have on the armature 2000 face conductors, each carrying 100 amperes, would require a very large armature, probably as large a diameter as was necessary in the former case; but then it was a question of carrying a large magnetic flux, which determined the size of the armature. In this case we should have a very large weight of armature copper, and though the other material would not cost much (if we look no further into the matter of field copper than relates to that necessary to obtain the required flux at no load), nevertheless, on the score of material alone, some intermediate number of conductors would be found to give a more economical result.

Influence of Armature Strength in these two Extreme Cases

In the first case, that of the armature with only five turns, three would have been but $\frac{5 \times 100}{2} = 250$ ampere-turns per pole-piece on the armature, which, as far as armature reaction effects are concerned, would

be entirely negligible; but, as relates to the collection of the current, there would be $\frac{500}{2.5} = 200$ average volts between commutator segments, and this would have corresponded to such a high inductance per coil as to have rendered quite impossible the reversal of 100 amperes, 20 times per second, with any ordinary arrangement of commutator and brushes.

In the other case (that of the machine with 1000 armature turns), there would have been one volt per turn, a value which, with the methods of construction generally employed, would correspond to a very low inductance indeed; but there would have been on the armature $\frac{1000 \times 100}{2} = 50{,}000$ ampere-turns per pole-piece, which would completely overpower the field excitation, and the design would be entirely out of the question.

We find, therefore, that while in the first case the armature strength is small, the voltage between segments is excessive. In the second case the voltage between segments is small; the armature is altogether too strong. With but two poles, some intermediate value would have to be sought for both quantities; probably something like 100 turns would give a fairly good result.

Conditions Essential to Sparkless Commutation

As a consequence of armature reaction and inductance, it becomes not only desirable but necessary to limit the armature strength to such an amount (at full load current) as shall not too greatly interfere with the distribution and amount of the magnetic flux set up by the magnet spools. It is furthermore necessary to make each armature coil between adjacent commutator segments of so low inductance as to permit of the complete reversal of the current by means of the residual flux in the commutating field. The location and amount of this residual flux is determined by the strength of the armature, and the position of the brushes and the reluctance of the gap. To best understand the method of fulfilling these conditions, attention should be given to the following illustrations, which lead up to a very definite method for assigning the most desirable electromagnetic proportions to constant potential dynamos, particularly with reference to the determination of the proper number of poles.

DETERMINATION OF THE NUMBER OF POLES FOR A GIVEN OUTPUT

Suppose we want a 50-kilowatt 400-volt bipolar generator. We conclude to limit the armature strength to 3000 ampere-turns per pole-piece, and the volts per commutator segment to 16 volts (a very high limit): Amperes output $= \frac{50,000}{400} = 125$ amperes. Therefore, each conductor carries $\frac{125}{2} = 62.5$ amperes. Turns per pole-piece $= \frac{3,000}{62.5} = 48$, *i.e.*, 96 total turns. $\frac{400}{16} = 25$ commutator segments between brushes, or 50 total commutator segments. Therefore $\frac{96}{50} =$ about two turns per coil (*i.e.*, per commutator segment).

In the 100 kilowatt machine for the same voltage, to retain the same strength of armature, and the same volts per commutator segment, we must have only one turn per coil.

For these values of armature strength and volts per commutator segment we have now reached the limiting output, and the problem arises What shall be done in the case of a machine of twice the size, in this case 200 kilowatts, if the type of winding remains the same? We cannot have less than one turn per commutator segment, so we find that in a bipolar machine it will be necessary to either double the armature strength, in which case we can retain the low voltage per commutator segment, or we can double the voltage per commutator segment, and keep the armature strength of the same low value used in the previous cases; or we can compromise by raising both limits to a less extent. This latter plan is that which would be adopted to retain the bipolar design. But the result would be unsatisfactory as regards sparking, and even though it could be made passable at this output, the same question would arise with the next larger size. But by the use of a multipolar design, the difficulty is entirely overcome. Suppose we let our 200-kilowatt 400-volt machine, have four poles. Then there will be four paths through the armature, each carrying a quarter of the total current. Amperes output $= \frac{200,000}{400} = 500$ amperes. Therefore, amperes per conductor $= \frac{500}{4} = 125$. The turns per pole-piece $= \frac{3000}{125} = 24$. We have, also, 24 commutator segments per pole-piece, giving $\frac{400}{24} = 16.6$ volts per commutator segment.

It might thus appear that a machine can be made to operate entirely satisfactorily as regards sparking, by designing it with a suitable number of poles. While this is the case over a wide range of speeds and voltages, certain difficulties are ultimately encountered with increasing speed, especially for machines of high voltage. A consideration of this must be reserved until after we have treated the subject of the "reactance voltage."

Multiple-Circuit Windings

With multiple-circuit windings, the armature strength and the volts per bar may be reduced to any desired extent by sufficiently increasing the number of poles, except in so far as limitations of cost, peripheral speed, and the practicable minimum width of segment, intervene. Thus, suppose that in a certain case the conditions given are that the armature strength of a 500-killowatt 600-volt generator shall be 4000 ampere-turns per pole-piece, and that there may be 15 volts per commutator segment. Then the number of poles would be determined as follows:

Commutator segments per pole-piece $\frac{600}{15} = 40.$

Therefore, 40 turns per pole-piece.

$\frac{4000}{40} = 100$ amperes per armature branch.

Full load current $\frac{500{,}000}{600} = 833$ amperes.

Therefore, we want $\frac{833}{100} = 8$ poles.

But suppose it were considered advisable that this generator should have only 3000 ampere-turns per pole-piece on the armature, and that it should have but 8 volts per commutator segment, then turns per pole-piece $= \frac{600}{8} = 75.$

Amperes per armature conductor $= \frac{3000}{75} = 40$

Therefore, number of poles $= \frac{833}{40} = 20.$

Two-Circuit Windings

But in the case of two-circuit windings, these values cannot be adjusted by changing the number of poles, for the reason that the current divides into two paths through the armature, independently of the number of poles, instead of dividing into as many paths as there are poles.

Suppose, for example, that it were desired to use a two-circuit winding

in a 500-kilowatt, 600-volt generator, and to have 15 volts per commutator segment. Then:

$$\text{Number of segments per pole-piece} = \frac{600}{15} = 40.$$

$$\text{Full load amperes} = \frac{500{,}000}{600} = 833.$$

$$\text{Amperes per turn} = \frac{833}{2} = 417.$$

Therefore, ampere-turns per pole-piece on armature $= 40 \times 417 = 16{,}700$.

This would be impracticable. To reduce this to 6000 ampere-turns, the turns have to be reduced, and consequently the commutator segments, to $\frac{6000}{16{,}700} \times 40 = 14$ per pole-piece. There would then be $\frac{600}{14} = 43$ volts per commutator segment, which, with ordinary construction, would correspond to so high a reactance voltage in the short-circuited coil (in a machine of this output) as not to be permissible. Moderate values can only be obtained by interpolating commutator segments in accordance with some well-known method, or by the use of double, triple, or other multiple windings. Such methods generally give unsatisfactory results, and two-circuit windings are seldom used for machines of large output. When they are used, in such cases, exceptional care has to be taken to counteract their objectionable features by the choice of very conservative values for other constants.

Multiple Windings

But the use of multiple windings (such, for instance, as the double winding of Fig. 74, page 73), permits of employing two-circuit windings.

Thus, suppose in the case of the design of a 350-kilowatt, 250-volt generator, it appears desirable, when considered with reference to cost of material, or for some other reason, to use 14 poles; and that, furthermore, a two-circuit multiple winding is to be used. The question arises, how many windings shall be employed, in order to have only 9 volts per commutator segment, and to permit not over 5000 ampere-turns per pole-piece on the armature?

$$\frac{250}{9} = 28 \text{ commutator segments per pole-piece.}$$

Therefore, 28 turns per pole-piece.

$$\text{Therefore, } \frac{5000}{28} = 180 \text{ amperes per turn.}$$

$$\text{Amperes output} = \frac{350{,}000}{250} = 1400 \text{ amperes,}$$

$$\frac{1400}{180} = 7.8.$$

Therefore, there must be eight paths through the armature from the positive to the negative brushes. Consequently, a two-circuit quadruple winding is required.

It may, however, be well to again emphasise the fact that poor results generally follow from the adoption of such windings, except in cases where a width of commutator can be afforded which permits of dispensing with all but two sets of brushes.[1] By adopting such a width of commutator, one of the savings effected by the use of multipolar designs is lost. By careful designing, two-circuit double and sometimes two-circuit triple windings have given good results.

Two-Circuit "Coil" Windings

But two-circuit single windings can be very properly applied to machines of such small capacity, that, when good constants are chosen, they work out to have one or more turns per segment. It follows that, within certain ranges, any desired values of armature strength and volts per commutator segment may be obtained; not, however, by a suitable choice of poles, but by the use of a suitable number of turns between commutator segments. Suppose, for instance, a 10-kilowatt 100-volt generator, with an armature strength of 2,000 ampere turns per pole-piece, and with 5 volts per commutator segment.

Then

$$\text{Segments per pole-piece} = \frac{100}{5} = 20$$

$$\text{Full load current} = \frac{10{,}000}{100} = 100 \text{ amperes.}$$

$$\text{Amperes per conductor} = \frac{100}{2} = 50.$$

$$\text{Turns per pole-piece} = \frac{2000}{50} = 40.$$

$$\text{Therefore,} \frac{40}{20} = \text{two turns per commutator segment.}$$

If 3,000 ampere-turns had been permissible, we should have used $\frac{3000}{2000} \times 2 = 3$ turns per commutator segment.

Finally, it may be stated that two-circuit armatures are built multi-

[1] If only two sets of brushes are retained, the short-circuited set of conductors no longer consists of the two corresponding to one turn, but now includes as many in series as there are poles. A high reactance voltage is consequently present in this short-circuited set. The presence of the full number of sets of brushes, if correctly adjusted, *should* reduce this, but cannot in practice be relied upon to do so.

polar mainly from considerations of cost, and should not be used for large outputs except in special cases.

Aside from the reasons dependent strictly upon the magnetic limit of output, it may be said that two-circuit windings are more or less unsatisfactory whenever the output is so large as to require the use of more than two sets of brushes (in order to keep the cost of the commutator, and the "reactance voltage"—to be discussed later—within reasonable limits), because of the two-circuit windings lacking the property of compelling the equal subdivision of the current among all the sets of brushes used. Selective commutation occurs, one set of brushes carrying for a time a large part of the total current; this set of brushes becoming heated. This trouble is greater the greater the number of sets of brushes, and the practicability of two-circuit windings may be said to be inversely as the number of poles. If, however, in *multiple* circuit windings the part of the winding opposite any one pole-piece should tend to take more than its share of the current, the increased armature demagnetisation and CR drop tends to restore equilibrium, this property constituting a great advantage.

Voltage per Commutator Segment as Related to Inductance

As already stated, the average voltage between commutator segments, although it can be relied on to give good results, if care is used in special cases, is not a true criterion of the inductance of a coil. For, in different types, this expression may have the same value for coils of different inductances.

Thus, if the design is for an armature in which the conductors are located in holes beneath the surface, the inductance will be very high, and it would be necessary to limit the average voltage per commutator segment to a very low value. If the slots are open, the inductance will be somewhat lower, and in a smooth core construction with the winding on the surface, the inductance is very low. In this latter case, a much higher value for the average volts per commutator segment could be used.

The possible value also varies according to whether carbon or copper brushes are used. Carbon[1] brushes may be much less correctly set and still have sparkless commutation, due to the high resistance of

[1] There has lately been a tendency amongst some designers to attribute still other properties to high-resistance brushes, and even to maintain that they play an important part,

the brush limiting extreme variation of current in the short-circuited coil; as well as because the brushes are not so subject to injury through this cause, as would be the case with copper brushes; consequently, the average volts per commutator segment may be permitted to be three or four times as great as with copper brushes, without endangering the durability either of the brushes or of the commutator; and on account of this, it is found desirable to increase the density in the air-gap to correspond with this higher inductance between commutator segments.

We have now shown that although the preliminary design for a commutating machine may be arrived at from the maximum permissible armature reaction and the number of commutator segments per pole necessary for good commutation, the average voltage between the commutator segments is not the ultimate expression as regards commutation. The ultimate expression must be in terms of the inductance of the coil or coils included between a pair of commutator bars.

In general, commutation occurs when a coil is in a feebly magnetised field, so that the inductance can be approximately calculated from the

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not only in limiting the short-circuit current, but in accelerating the building up of the reversed current. However, one would feel inclined to hold that the main element in the commutating, *i.e.*, stopping and reversing of the current, is attributable to the influence of the residual commutating field; and that while the carbon brush aids in promptly arresting the original current, it is perhaps of still more importance in virtue of its possessing a certain inertness in combination with the copper commutator segments which renders the sparking much less destructive than between copper brushes and copper segments. It has the property of burnishing the commutator, giving it a lustrous refractory surface.

The following bibliography comprises the most recent contributions to the discussion of the subject of sparking in commutating dynamos :—

Reid.—"Sparking: Its Cause and Effects." Am. Inst. Elec. Engrs.; December 15th, 1897. Also *The Electrician*, February 11th, 1898.

Thomas.—"Sparking in Dynamos." *The Electrician*, February 18th, 1898.

Girault.—"Sur la Commutation dans les Dynamos à Courant Continu." *Bull. de la Soc. Int. des Electr.*, May, 1898, vol. xv, p. 183.

Dick.—"Ueber die Ursachen der Funkenbildung an Kollektor und Bürsten bei Gleichstrom-Dynamos." *Elek. Zeit.*, December 1st, 1898, vol. xix, p. 802.

Fischer-Hinnen.—Ueber die Funkenbildung an Gleichstrom-Maschinen." *Elek. Zeit.*, December 22nd and 29th, 1898, vol. xiv, pp. 850 and 867.

Arnold.—"Die Kontactwiderstand von Kohlen und Kupferbürsten und die Temperaturerhohung eines Kollektors." *Elek. Zeit.*, January 5th, 1899, vol. xx, p. 5.

Kapp.—Die Funkengrenze bei Gleichstrom-Maschinen." *Elek. Zeit.*, January 5th, 1899, vol. xx, p. 32.

Arnold and Mie.—"Ueber den Kurschluss der Spulen und die Kommutation des Stromes eines Gleichstromankers." *Elek. Zeit.*, February 2nd, 1899, vol. xx, p. 97.

magnetomotive force of the coils, and the reluctance of the magnetic circuit around which the coils act. The frequency of reversal is determined from the brush and the commutator speed.

The commutated current consists of two components: one a wattless magnetising component, and the other an energy current, due firstly to the dissipation of energy by $C^2 R$ loss in the coil, and secondly to eddy currents generated internally in the copper conductors, and in the surrounding mass of metal.

It follows from this that there is a loss increasing with the load in commutating machines due to the commutation of the currents. There are also other load losses in commutating machines, brought about by the distortion and the increasing magnetisation in the iron, so that the hysteresis and eddy current losses increase from no load to full load, as also the eddy current losses in the armature conductors themselves.[1] It has been generally assumed on the part of designers that these losses in the armatures of commutating dynamos do not increase with the load. This, however, is incorrect. The increase does exist, and is in general of

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Hobart.—"Modern Commutating Dynamo Machinery, with Special Reference to the Commutating Limits." *Proc.* Inst. Elec. Engrs., 1901, vol., xxxi. p. 170.

Alexander Rothert.—"Wie viel Kollektorlamellen soll eine Gleichstrommaschine haben?" *Elek. Zeit.*, 1902, Heft. 15, p. 309.

Emil Dick.—"Funkenlose Kommutirung." *Elek. Zeit.*, 1902, Heft. 18, p. 369.

E. Arnold.—"Beitrag zur experimentellen Untersuchung von Gleichstrommaschinen." *Elek. Zeit.*, 1902, Heft. 25, p. 469.

Karl Pichelmeyer.—"Zur Theorie der Stromwendung." *Elek. Zeit.*, 1902, Heft. 29, p. 623.

Franklin Punga.—"Beitrag zur Theorie der Stromwendung." *Zeit. für Elek.*, 1902, Heft. 30, 31, 32.

Friedrich Eichberg.—"Ueber kompensirte Gleichstrommaschinen." *System Deri*, 1902, Heft. 37, p. 817.

Alexander Rothert.—"Beitrag zur Theorie der Stromwendung." *Elek. Zeit.*, 1902, Heft. 39, p. 865.

P. Prenzlin.—"Ueber funkenfreies Kommutiren des Stromes von Gleichstrommaschinen mit Kohlenbürsten bei Vor-und Rücklauf der Maschine und konstanter Bürstenstellung in der neutralen Linie." *Elek. Zeit.*, 1902, Heft. 43, p. 933.

Karl Czeija.—"Kommutationsvorgänge in Gleichstrommaschinen." *Sammlung Elektrotechnischer Vorträge*, Stuttgart, Ferd. Euke, 1903.

Adolf Railing.—Ueber Kommutierungsvorgänge und zusätzliche Bürstenverluste." *Sammlung Elektrotechnisher Vorträge*, Stuttgart, Ferd. Euke, 1903.

Karl Pichelmeyer.—"Die Stromwendung in Kommutirenden Maschinen." *Zeit. für Elek.*, 1904, Heft., 1, p. 1.

Franklin Punga.—"Das Funken von Kommutatormotoren, mit besonderer Berücksichtigung der Einphasen-Kommutatormotoren. Hannover, Gebr. Jänecke.

[1] See Fig. 114, on page 110, for experimental confirmation of this statement.

the same nature as the increase in these losses in alternators, due to the load, although they may be restricted to a greater extent by proper designing. The effect of the induced eddy currents on commutation is often appreciable, since the frequency of commutation is generally from 200 to 700 cycles per second. For this reason, calculations on inductance in reference to commutation have to be considered with reference to the particular construction of the armature core. Constants as to inductance are, therefore, best determined by actual measurements. In practice, a good average expression is, that one ampere turn will give a field of 20 C.G.S. lines per inch of length of armature core.[1]

It is convenient to assume this as a basis upon which to work out a design. As the design develops, the figures should be corrected according to the dimensions selected. This is the most satisfactory method, and several tests will be described, the results of which have a direct bearing upon the value of the constant. By a study of these results one may determine the most desirable proportions to give to the armature slot in order to bring the inductance down to, or even below, the value of 20 C.G.S. lines per ampere turn and per inch of length of armature lamination. In cases where it is impracticable to use such slot proportions as shall give the minimum value, the tests afford an indication of the value to be used. It is, of course, very desirable that such experiments should be independently carried out on the particular line of commutating dynamo with which the individual designer is concerned. In this connection, that is, in relation to inductance in commutating dynamos, interest attaches, not to the inductance of the armature winding as a whole, as in the case of alternating-current dynamos,[2] but to the inductance of those components of the winding which simultaneously undergo commutation at the brushes. In well-designed dynamos of this

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[1] This method has subsequently been developed by one of the authors (see *Proc.* Inst. Elec. Engrs., 1901, vol. xxxi., p. 170; and also "Technics," vol. i, page 60, *et seq.*, to a greater degree of exactness, by dividing the inductance into the two components associated respectively with the end connections ("free length") and the slot portions ("embedded length"). While this method is preferable, and is now widely employed, it would not have materially modified the conclusions arrived at in the present treatise, and hence the original method is adhered to in this edition.

[2] Rotary converters contain the elements of both these types, and in their subsequent treatment it will appear that, while the coil undergoing commutation should have the least practicable inductance, the inductance of the coils in series between collector rings must have a suitable value, for reasons entirely other than those related to commutation.

type such coils will, at the time of commutation, be located in the space between pole-tips, practically at the position of minimum inductance. The measurement of this inductance was the object of the tests now to be described.

Practical Definition of Inductance

A coil has an inductance of one henry when it is situated in a medium of such permeability, and is so dimensioned that a current of one ampere sets up a magnetic flux of such a magnitude that the product of the number of lines linked with the coil, by the number of turns in the coil, is equal to 100,000,000. If the coil has but one turn, then its inductance, expressed in henrys, becomes 10^{-8} times the number of lines linked with the turn when one ampere is passing through it. If the coil has T turns, then not only is the magnetomotive force T times as great (except in so far as saturation sets in), but this flux is linked with T turns; hence the product of flux and turns, *i.e.*, the total linkage, the *inductance* of the coil, is proportional to the square of the number of turns in the coil.

Description of Experimental Tests of Inductance

First Experiment.—In Fig. 161 is shown a sketch of a commutating dynamo with a projection type of armature with a four-circuit single winding. The inductance of several groups of coils was measured with a 25-cycle alternating current, and the results, together with the steps of the calculation, are set forth in the following Tables.

Table XLI.—Minimum Inductance

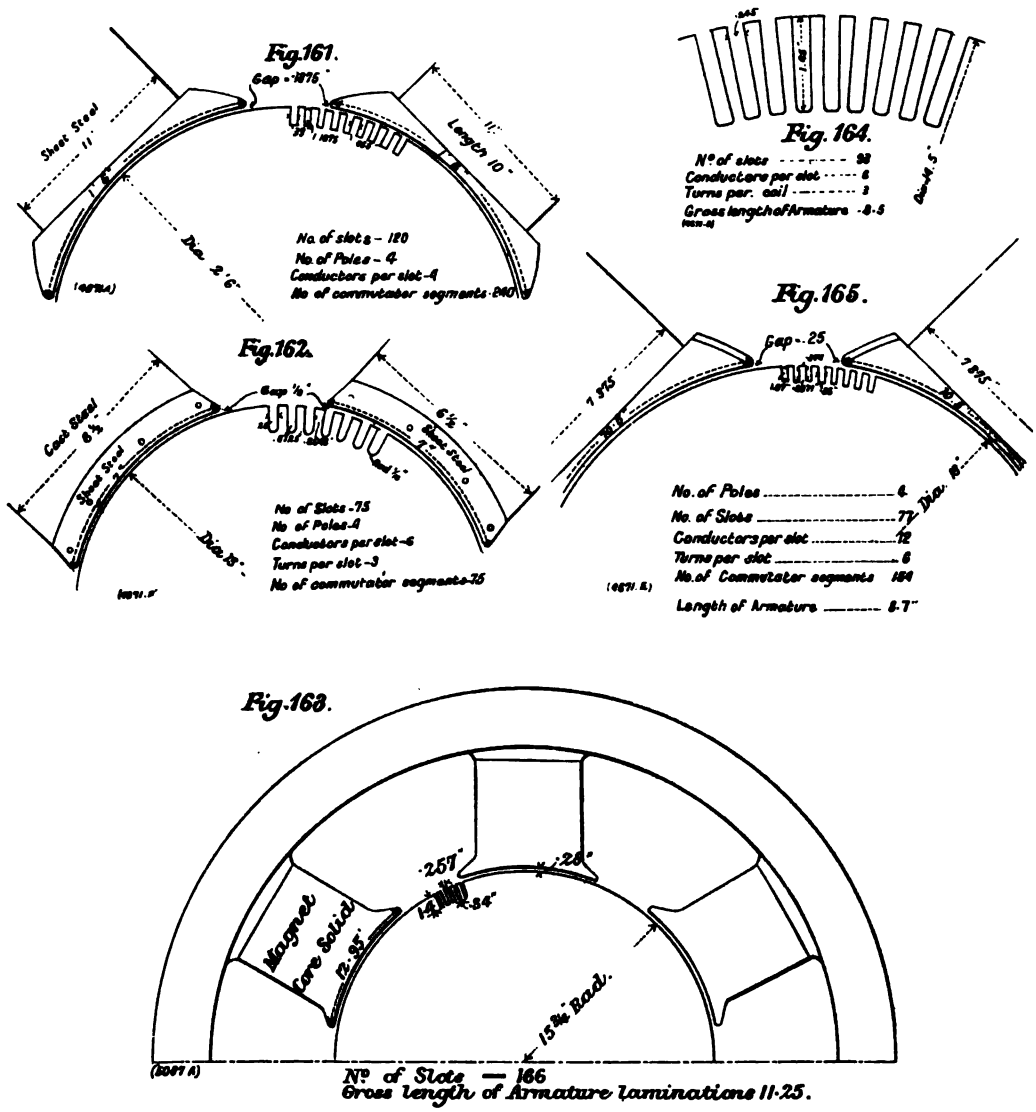
Conductors in position of minimum inductance are in the commutating zone, *i.e.*, midway between pole corners.

Number of Turns Under Test.	Amperes in these Turns.	Volts.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch of Length of Lamination.
4	75	.594	00790	.00692	.00388	.0000247	15.0
5	65	.728	.0120	.00865	.00708	.0000450	18.0
6	68	.944	.0139	.0104	.00930	.0000592	16.5

The air gap of this machine was afterwards shortened from its original depth of about .188 in. to about .1 in., and the inductance in the position of

maximum inductance was again measured. In the position of minimum inductance, the values are unaffected by the depth of the air gap.

Second Experiment.—A commutating dynamo, illustrated in Fig. 162,



FIGS. 161 TO 165. DIAGRAMS ILLUSTRATING TESTS OF INDUCTANCE

has a four-circuit single winding consisting of 75 coils of three turns each, arranged in 75 slots. Tests with 25-cycle alternating current were made on the inductance of from one to five adjacent coils, and the results are set forth in Table XLIV.

TABLE XLII.—MAXIMUM INDUCTANCE

Conductors in position of maximum inductance are under the middle of the pole-faces.

Number of Turns Under Test.	Amperes in these Turns.	Volts.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch of Length of Lamination.
2	73	.391	.00535	.00346	.00407	.0000260	65.0
3	71	.730	.0103	.00529	.00890	.0000567	63.0
4	60 23	1.096 .378	.0174	.00692	.0159	.000102	63.5
5	22	.594	.0270	.00865	.0256	.000163	65.0
6	22	.770	.0350	.0104	.0333	.000212	59.0

TABLE XLIII.—CONDUCTORS IN POSITION OF MAXIMUM INDUCTANCE WITH SHORTENED AIR GAP

Number of Turns Under Test.	Amperes in these Tests.	Volts.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C. G. S. Lines per Ampere Turn and per Inch of Length of Lamination.
1	80.5	.189	.00235	.00173	.00138	.00000876	87.6
2	40.0	.230	.00575	.00346	.00452	.0000288	72.0
2	78.0	.472	.00605	.00346			
3	20.5	.256	.0125	.00519	.0116	.0000735	81.5
3	39.0	.500	.0128	.00519			
3	76.5	1.02	.0133	.00519			
4	20.5	.432	.0210	.00692	.0202	.000129	80.5
4	38.0	.850	.0224	.00692			
5	19.5	.640	.0328	.00865	.0315	.000200	80.0
6	19.7	.915	.0465	.0104	.0452	.000288	80.0

Hence shortening the air gap has increased the inductance in the position of maximum inductance by about 27 per cent.

TABLE XLIV.—POSITION OF MINIMUM INDUCTANCE

Number of Coils Under Test.	Number of Turns Under Test.	Amperes.	Volts.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch of Length of Lamination.
3	9	63	2.25	.0357	.0309	.0173	.000110	15.5
4	12	58	3.00	.0518	.0412	.0308	.000197	15.6
5	15	52	3.70	.0710	.0515	.0482	.000307	15.6
				Position of Maximum Inductance				
1	3	61	.75	.0123	.0103	.00655	.000042	53
2	6	58	1.95	.0339	.0206	.0268	.000171	54
3	9	52	3.45	.0668	.0309	.0590	.000376	53
4	12	21	2.30	.111	.0412	.103	.000655	52
5	15	20	3.20	.165	.0515	.156	.00099	50

Attention should again be drawn to the fact that it is the minimum inductance, which corresponds to the inductance in the position of commutation, which is of chief interest in the present section.

Tables XLII. and XLIII., and the last half of Table XLIV., relating to the position of maximum inductance, are useful for a correct understanding of the relation of the proportions of the magnetic circuit of the armature coil to the resulting inductance, but are not directly applicable to the conditions obtaining during commutation.

Third Experiment.—Tests were made with 60-cycle alternating current upon the inductance of a six-pole commutating generator, the armature of which had 166 slots with a six-circuit single-winding of 166 complete coils, each of two turns. Fig. 163, page 176, gives the dimensions. The results are set forth in Table XLV.

TABLE XLV.—POSITION OF MINIMUM INDUCTANCE

Number of Coils Under Test.	Number of Turns Under Test.	Amperes.	Volts.	Impedance in Ohms.	Mean Impedance.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Length of Armature Lamination.
1	2	98.5	.46	.00467					
1	2	126.5	.585	.00463	.00465	.0015	.00439	.0000117	26.0
2	4	85.0	1.42	.0167					
2	4	95.7	1.62	.0169	.0168	.0030	.0165	.0000440	24.5
2	4	105.	1.79	.0169					
3	6	65.3	2.24	.0343					
3	6	75.0	2.60	.0346	.0345	.0045	.0342	.000091	21.8
3	6	87.0	3.00	.0345					
4	8	65.5	3.74	.0571					
4	8	76.0	4.36	.0573	.0573	.0060	.0570	.000152	21.1
4	8	87.0	5.00	.0575					
				Position of Maximum Inductance					
1	2	89.8	.71	.0078					
1	2	95.2	.77	.0081	.0080	.0015	.0078	.0000208	46.3
1	2	111.8	.91	.0081					
2	4	71.0	2.24	.0316					
2	4	78.0	2.42	.0310	.0312	.0030	.0310	.000082	45.6
2	4	84.2	2.60	.0309					
3	6	72.3	4.68	.0648					
3	6	83.7	5.38	.0643	.0644	.0045	.064	.000170	42.0
3	6	89.3	5.74	.0643					
4	8	66.6	7.14	.1072					
4	8	77.0	8.32	.1062	.1052	.0060	.105	.000279	38.8
4	8	86.3	8.9	.1032					

Fourth Experiment.—This relates to the carcass of a 30 horse-power railway armature, the leading dimensions of which are indicated in Fig. 164, page 176. Only four coils, of three turns each, were in position in four adjacent armature slots. The armature was out of its field frame, which was equivalent to its being in the position of minimum inductance. The testing current was supplied at a frequency of 100 cycles per second. Gross length of armature lamination = 8.5 in. The results obtained are set forth in the following Table :

TABLE XLVI.—POSITION OF MINIMUM INDUCTANCE

Number of Coils Under Test.	Number of Turns in these Coils.	Amperes in these Turns.	Volts at Terminals.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Gross Length of Armature Lamination.
1	3	55.5	1.11	.0200	.0085	.0181	.0000286	37.4
1	3	47.0	.94	.0200	.0085	.0181	.0000286	37.4
1	3	34.0	.68	.0201	.0085	.0182	.0000287	37.5
1	3	31.5	.62	.0195	.0085	.0176	.0000278	37.7
2	6	51.9	2.78	.0536	.017	.0507	.000080	26.2
2	6	42.5	2.27	.0536	.017	.0507	.000080	26.2
2	6	36.3	1.97	.0542	.017	.0513	.000081	26.2
2	6	31.4	1.71	.0545	.017	.0517	.000082	26.7
3	9	23.7	2.27	.0960	.026	.0924	.000147	21.4
3	9	18.9	1.84	.0974	.026	.0937	.000149	21.6
3	9	16.9	1.62	.0959	.026	.0921	.000146	21.2
3	9	15.8	1.50	.0947	.026	.0910	.000145	21.1
4	12	19.8	2.91	.147	.034	.143	.000227	18.5
4	12	15.9	2.51	.158	.034	.154	.000245	20.0
4	12	14.4	2.15	.149	.034	.145	.000230	18.8
4	12	12.4	1.88	.152	.034	.148	.000235	19.2

Mean of the four observations for three turns 37.5
,, ,, six ,, ... 26.4
,, ,, nine ,, ... 21.3
,, ,, twelve ,, ... 19.1

Fifth Experiment.—Fig. 165, page 176, gives a sketch showing the leading dimensions of the dynamo experimented upon. The armature was in place in the cast-steel frame. Testing current had a periodicity of 100 cycles per second. The gross length of the armature lamination = 8.7 in. The results are given in Table XLVII.

TABLE XLVII.—POSITION OF MINIMUM INDUCTANCE

Number of Coils Under Test.	Number of Turns in these Coils.	Amperes in these Turns.	Volts at Terminals.	Impedance in Ohms.	Resistance in Ohms.	Reactance in Ohms.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Gross Length of Armature Lamination.
1	3	39.0	.838	.0215	.0065	.0205	.0000330	42.2
1	3	43.5	.941	.0216	.0065	.0206	.0000332	42.4
1	3	46.0	.992	.0216	.0065	.0206	.0000332	42.4
2	6	20.0	1.18	.0590	.0130	.0584	.0000924	29.5
2	6	21.5	1.24	.0577	.0130	.0562	.0000895	28.6
2	6	24.0	1.39	.0580	.0130	.0565	.0000900	28.8
2	6	25.0	1.45	.0581	.0130	.0565	.0000900	28.8
3	9	14.9	1.84	.124	.0195	.122	.000194	27.6
3	9	16.9	2.05	.122	.0195	.120	.000191	27.2
3	9	18.9	2.29	.122	.0195	.120	.000191	27.2
3	9	20.9	2.52	.121	.0195	.119	.000190	26.9
4	12	13.4	2.46	.184	.026	.182	.000290	23.2
4	12	14.8	2.74	.185	.026	.183	.000291	23.3
4	12	15.8	3.01	.190	.026	.188	.000299	23.9
4	12	18.3	3.44	.188	.026	.186	.000296	23.7

Mean of the observations with three turns	42.3
" " six "	28.9
" " nine "	27.2
" " twelve "	23.5

Sixth Experiment.—This experiment was made in respect to the inductance of an armature of a 25 horse-power tramway motor.

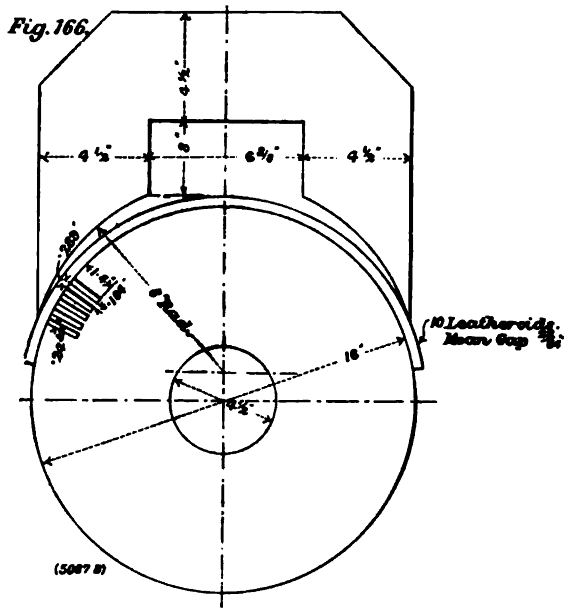
The following data applies to this armature:—

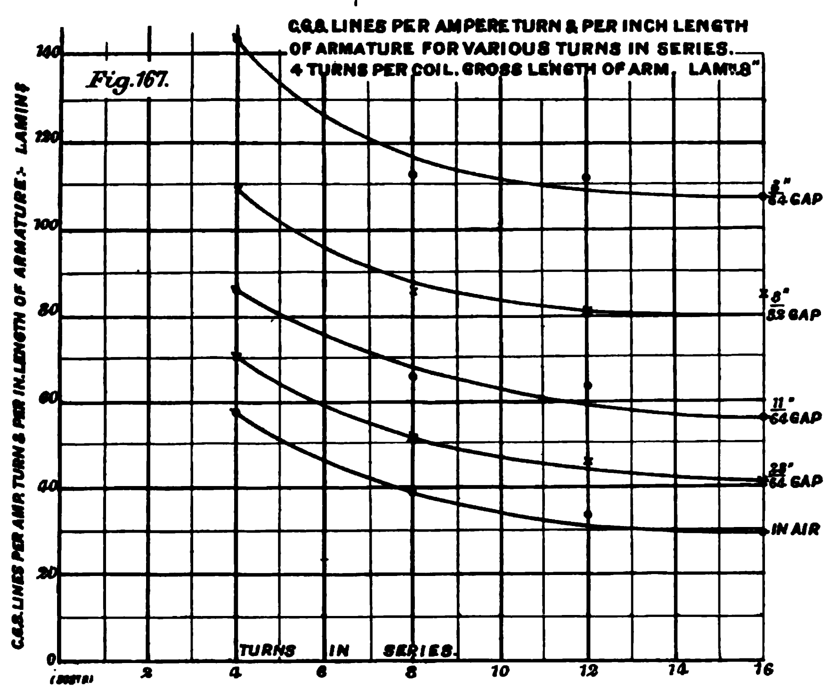
Diameter of armature	16 in.
Number of slots	105
" coils	105
Turns per coil	4
Conductors per slot	12
Gross length of armature laminations	8 in.

The inductance tests were made with a current of a periodicity of 100 cycles per second.

Inductance measurements were made upon one, two, three, and four coils in series, and under the condition of minimum inductance, which was considered to correspond with the armature in air, and then with air gaps of various lengths arranged by a special pole-piece of laminated iron of the dimensions shown in Fig. 166, on page 181, which shows the pole-piece in place, with pieces of leatheroid between it and the armature. Owing to this pole-piece being of the same radius as the

armature, on inserting the leatheroids a gap was obtained which was larger at the inner edge of the pole-piece than at the outer (see Fig. 166), so that in the calculations and curves a mean gap is given.





FIGS. 166 AND 167.—DIAGRAMS ILLUSTRATING TESTS OF INDUCTANCE

In Tables XLVIII. to LI. inclusive, and in the curves of Figs. 167 and 168, are given the results of these tests.

TABLE XLVIII.—ONE COIL OF FOUR TURNS PER COIL. RESISTANCE = 0.014 OHMS.

Amperes.	Volts.	Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C.G.S. Lines Per Ampere Turn and per Inch Length of Armature.	Mean.	Mean Air Gap. in.
23.75	1.08	.0455	.0433	97	.0000710	55.5		
23	1.07	.0466	.0444	97	.0000728	57.0	56.6	∞
20.2	.945	.0468	.0466	97	.0000732	57.2		
23.5	1.325	.0562	.0549	99	.0000884	69.0		
22	1.268	.0576	.0558	99	.0000897	70.0	69.8	$\frac{23}{64}$
19.75	1.120	.0568	.0551	99	.0000887	69.3		
20	1.385	.0693	.0678	99	.000109	85.2		
22.5	1.56	.0694	.0679	99	.000109	85.2	85.5	$\frac{11}{64}$
24	1.675	.0698	.0684	99	.000110	86.0		
24.5	2.18	.0891	.0880	99	.000141	110.0		
20	1.725	.0863	.0852	99	.000137	107.0	108.2	$\frac{3}{32}$
22	1.91	.0868	.0857	99	.000138	107.8		
22	2.53	.1151	.1141	99	.000189	143.6		
20	2.29	.1145	.1137	99	.000183	143.0	142.5	$\frac{3}{64}$
18	2.03	.1128	.1119	99	.000180	141.0		

TABLE XLIX.—TWO COILS OF FOUR TURNS PER COIL. RESISTANCE = 0.033 OHMS.

Amperes.	Volts.	Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Length of Armature.	Mean.	Mean Air Gap. in.
21	2.64	.1256	.1212	99	.000195	38.1		
19	2.42	.1274	.1230	99	.000198	38.7	38.2	∞
17.5	2.18	.1245	.1202	99	.000193	37.8		
17	2.85	.1676	.1645	100	.000262	51.3		
15.5	2.61	.1680	.1646	100	.000262	51.3	51.0	$\frac{23}{64}$
13	2.15	.1655	.1620	100	.000258	50.4		
13	2.81	.216	.213	100	.000340	66.4		
15	3.20	.213	.210	100	.000334	65.3	65.9	$\frac{11}{64}$
16.5	3.55	.215	.212	100	.000338	66.1		
12.5	3.48	.278	.276	100	.000440	86.0		
11	3.03	.275	.273	100	.000435	85.0	85.6	$\frac{3}{32}$
10	2.77	.277	.275	100	.000438	85.8		
10	3.59	.359	.358	99	.000576	112.5		
9	3.20	.356	.355	99	.000572	111.7	111.6	$\frac{3}{64}$
8	2.82	.353	.352	99	.000567	110.7		

Table L.—Three Coils of Four Turns per Coil. Resistance = .0473 Ohms.

Amperes.	Volts.	Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Length of Armature.	Mean.	Mean Air Gap.
								in.
15	3.68	.245	.240	99	.000386	33.5		
13.5	3.35	.248	.243	99	.000391	33.9	33.7	∞
12	2.96	.246	.241	99	.000388	33.7		
10	3.47	.347	.344	98	.000558	48.5		
9	2.98	.331	.328	98	.000553	46.3	45.8	$\frac{23}{64}$
8	2.45	.306	.303	98	.000492	42.7		
17	7.8	.458	.452	98	.000737	63.8		
15	6.75	.450	.447	98	.000726	63.0	63.2	$\frac{11}{64}$
14	6.3	.450	.447	98	.000726	63.0		
13	7.84	.603	.601	98	.000976	84.6		
12	7.08	.590	.588	98	.000958	83.3	80.8	$\frac{3}{32}$
10	5.32	.532	.530	98	.000863	74.7		
18	14.6	.812	.811	98	.001317	114.2		
16	12.5	.782	.781	98	.001270	110.1	111.1	$\frac{3}{64}$
15	11.6	.774	.773	98	.001255	109.0		

Table LI.—Four Coils of Four Turns per Coil. Resistance = .0637 Ohms.

Amperes.	Volts.	Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Length of Armature.	Mean.	Mean Air Gap.
								in.
19	7.42	.390	.385	100	.000613	29.9		
17	6.47	.380	.375	100	.000598	29.3	29.5	∞
14	5.32	.380	.375	100	.000598	29.3		
15	8.23	.544	.539	100	.000872	42.6		
13	7.06	.543	.538	100	.000871	42.6	41.5	$\frac{23}{64}$
11	5.48	.500	.495	100	.000802	39.2		
10	7.58	.758	.755	100	.00120	58.7		
9	6.64	.738	.735	100	.00117	57.3	56.1	$\frac{11}{64}$
8	5.40	.672	.672	100	.00107	52.3		
17	19.04	1.12	1.117	100	.00178	87.0		
15	16.25	1.082	1.079	100	.00172	84.2	84.8	$\frac{3}{32}$
13	13.75	1.057	1.054	100	.00170	83.2		
17	24.0	1.411	1.410	100	.00225	110		
15.5	21.3	1.375	1.374	100	.00219	107	107.5	$\frac{3}{64}$
14	19.0	1.356	1.355	100	.00216	105.5		

The curves in Figs. 167 and 168 are plotted from the above results.

No results are given for the position of zero air gap, since great inaccuracy was introduced by the pole-piece not making a uniform magnetic contact each time it was replaced.

Seventh Experiment.—The armature of a 20 horse-power railway motor characterised by an especially small number of slots (twenty-nine) was measured as to inductance; and it is interesting to note that despite the concentration of many turns in each slot, the inductance as expressed in terms of the number of C.G.S. lines per ampere turn and per inch

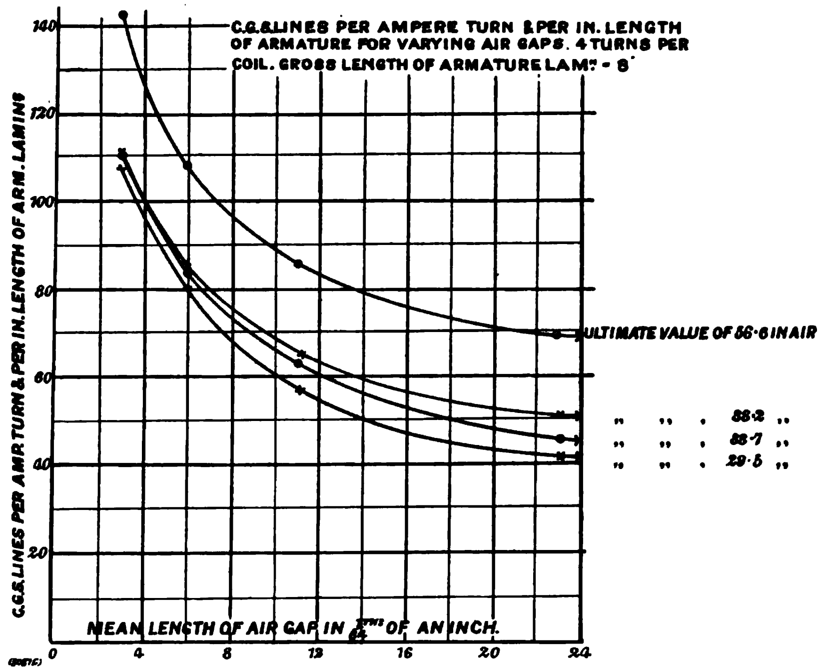


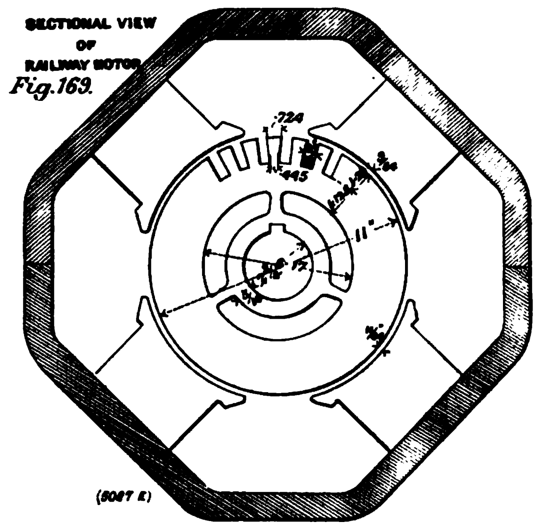
FIG. 168.—DIAGRAM ILLUSTRATING TESTS OF INDUCTANCE

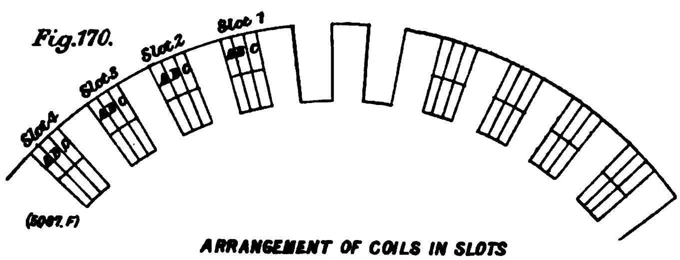
length of armature lamination, is but very little greater than in machines with many slots and but few conductors per slot.

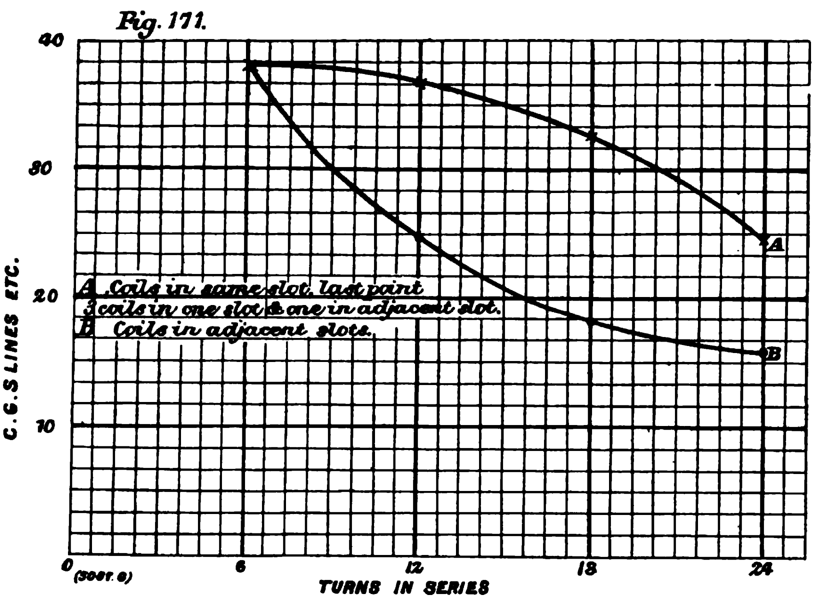
The principal dimensions of the armature are given below, and in Fig. 169, page 185.

Diameter of armature	11 in.
Number of segments	29
„ coils	87
Turns per coil	6
Conductors per slot	36
Gross length of armature laminations	9 in.
Length of air gap average...	$\frac{5}{32}$ in.

The values for the position of minimum inductance were taken with the armature out of its frame; *i.e.*, in air.







FIGS. 169 TO 171.—DIAGRAMS OF 20 HORSE-POWER MOTOR AND TEST CURVES.

For the position of maximum inductance, the armature was in its frame with the coils under test directly under the pole-face. The pole-face was built of laminations.

Fig. 170 shows the arrangement of the coils in the slots, and also serves as a key to the combinations of coils taken. Taking slot 1, it was found that the inductance of coils A, B, and C were practically the same.

The results are plotted in Fig. 171. In the curve marked A, the turns are situated in one and the same slot except for the last point (*i.e.*, twenty-four turns), in which case, eighteen turns were in one slot and six turns in the adjacent one. In curve B, the turns were situated six in each slot (*i.e.*, one coil per slot), the slots being adjacent.

The observations are given below in tabulated form.

TABLE LII.

Amperes.	Volts.	Impedance.	Mean Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C.G.S. Lines per Ampere Turn and per Inch Length of Armature.
One Coil of 6 Turns. Position of Minimum Inductance							
Slot 1, Coil B. Resistance = .0230 ohms.							
15	—	.0793					
17	—	.0782	.0786	.0752	97	.0001237	38.2
19	—	.0784					
Two Coils of 6 Turns per Coil. Position of Minimum Inductance							
Slot 1, Coils B and C. Resistance = .048 ohms.							
8	—	.299					
10	—	.290	.293	.289	97	.000476	36.7
11	—	.291					
Slot 1, Coil B. Slot 2, Coil B. Resistance = .049 ohms.							
10	—	.204					
13	—	.199	.199	.195	96	.000322	24.8
15	—	.195					
Three Coils of 6 Turns per Coil. Position of Minimum Inductance							
Slot 1, Coils A, B, and C. Resistance = .0738 ohms.							
9	5.78	.643					
11	6.68	.607	.614	.609	97	.0010	34.3
13	7.7	.593					
Slot 1, Coils A and B. Slot 2, Coil B. Resistance = .0722 ohms.							
13	5.26	.404					
15	6.52	.407	.412	.405	96	.000673	23.1
17	7.23	.426					
Slot 1, Coil B. Slot 2, Coil B. Slot 3, Coil B. Resistance = .0722 ohms.							
13	4.4	.338					
15	5.08	.339	.338	.330	96	.000548	18.1
17	5.72	.336					

TABLE LII.—*Continued*

Amperes.	Volts.	Impedance.	Mean Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys	C.G.S. Lines per Ampere Turn and per Inch Length of Armature.
Four Coils of 6 Turns per Coil. Position of Minimum Inductance							
Slot 1, Coils A, B, and C. Slot 2, Coil B. Resistance = .0976 ohms.							
13	10.17	.782					
15	11.5	.767	.772	.765	96	.001272	24.6
17	13.78	.769					
Slot 1, Coil A and B. Slot 2, Coils A and B. Resistance = .098 ohms.							
8	6.02	.752					
9.5	6.97	.732	.743	.736	96	.001223	23.6
10.5	7.62	.746	.74				
Slot 1, Coils A and B. Slot 2, Coil B. Slot 3, Coil B. Resistance = .0984 ohms.							
8.5	5.45	.642					
10	6.27	.627	.626	.620	97	.001020	19.7
12	7.30	.608					
Slot 1, Coil B. Slot 2, Coil B. Slot 3, Coil B. Slot 4, Coil B. Resistance = 0894 ohms.							
10	5.25	.525					
13	6.65	.512	.511	.501	97	.000824	15.9
15	7.47	.498					
One Coil of 6 Turns. Position of Maximum Inductance							
Slot 1, Coil B. Resistance = .0232 ohms.							
15	2.16	.144					
13	1.89	.145	.144	.142	101	.000224	69.2
10	1.42	.142					
Two Coils of 6 Turns per Coil. Position of Maximum Inductance.							
Slot 1, Coils B and C. Resistance = .0649 ohms.							
10	5.6	.56					
9	4.94	.55	.553	.551	100	.000877	67.7
8	4.4	.55					
Slot 1, Coil B. Slot 2, Coil B. Resistance = .0479 ohms.							
10	4.35	.435					
11	4.81	.437	.438	.436	101	.000687	53.0
12	5.32	.443					
Three Coils of 6 Turns per Coil. Position of Maximum Inductance.							
Slot 1, Coils A, B, and C. Resistance = .0735 ohms.							
15	19.2	1.28					
14	18	1.28	1·28	1.28	102	.0020	68.9
13	16.6	1.28					
Slot 1, Coils A and B. Slot 2, Coil B. Resistance = .0748 ohms.							
9	9.6	1.07					
10	10.0	1.07	1.07	1.07	101	.00169	58.3
11	11.85	1.08					

TABLE LII.—*Continued.*

Amperes.	Volts.	Impedance.	Mean Impedance.	Reactance.	Cycles per Second.	Inductance in Henrys.	C. G. S. Lines per Ampere Turn and per Inch Length of Armature.
Slot 1, Coil B. Slot 2, Coil B. Slot 3, Coil B. Resistance = .0739 ohms.							
11	9.2	.837					
12	10	.834	.835	.830	97	.00136	46.8
13	10.85	.835					
Four Coils of 6 *Turns per Coil. Position of Maximum Inductance*							
Slot 1, Coils A, B, and C. Slot 2, Coil B. Resistance = .0984 ohms.							
12	23.3	1.94					
13	25.3	1.95	1.94	1.94	103	.0030	59.2
14	27.3	1.95					
Slot 1, Coils A and B. Slot 2, Coils A and B. Resistance = .0992 ohms.							
12	22.4	1.87					
13	24	1.85	1.85	1.85	101	.00292	57.6
15	27.6	1.84					
Slot 1, Coils A and B. Slot 2, Coil B. Slot 3, Coil B. Resistance = .101 ohms.							
13	20.7	1.59					
15	23.6	1.57	1.57	1.57	101	.00247	48.7
17	26.5	1.56					
Slot 1, Coil B. Slot 2, Coil B. Slot 3 Coil B. Slot 4, Coil B. Resistance = .0986 ohms.							
15	19.6	1.31					
16	20.9	1.31	1.31	1.31	101	.00206	40.6
17	22.2	1.31					

Eighth Experiment.—These measurements related to an armature of an alternating-current dynamo. The considerable number of slots, however, make the results instructive from the standpoint of commutating machines. First, the coils A A and B B of Fig. 172 were connected in series, and the inductance was measured at a periodicity of 30 cycles in the position of minimum and maximum inductance, the position shown in Fig. 172 being, of course, the position of maximum inductance.

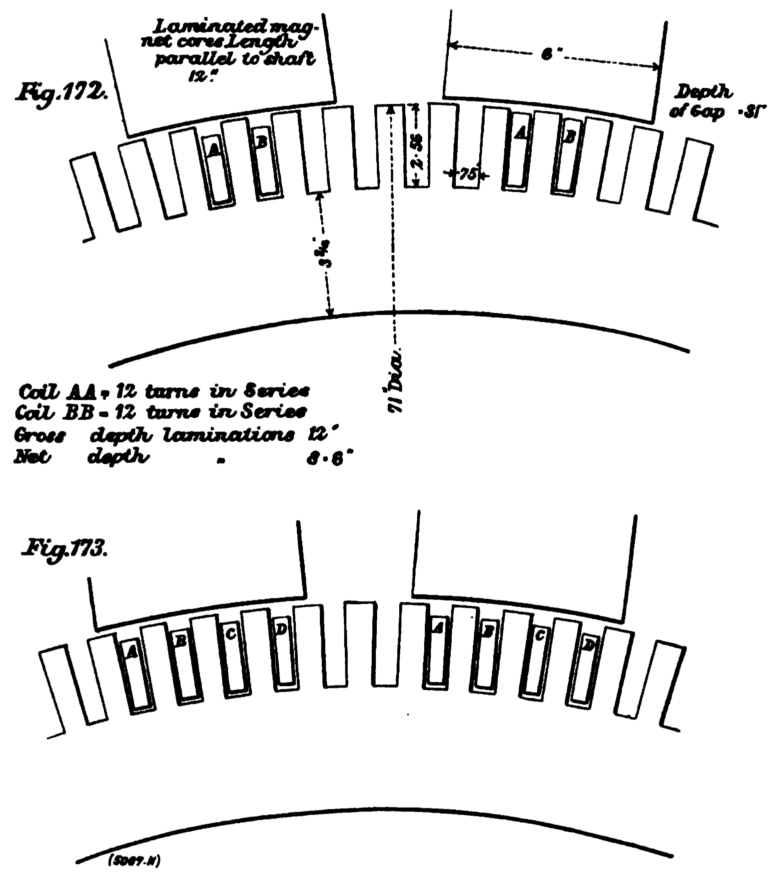
The values deduced from the observations were :—

Position of minimum inductance	... ...	20. C.G.S. lines per ampere turn and per inch gross length of armature lamination.
„ maximum inductance	... ...	35. „ „ „

Then the turns in four adjacent slots were connected in series, and then, as shown in Fig. 173, inductance was measured in the positions

of minimum and maximum inductance. The following results were obtained :—

Position of minimum inductance	... ...	13. C.G.S. lines per ampere turn and per inch gross length of armature lamination.
,, maximum inductance	... ...	19. ,, ,, ,,



FIGS. 172 AND 173. TESTS ON AN ALTERNATOR ARMATURE

A study of these tests indicates that in projection armatures it is practicable to so proportion the slots and conductors as to obtain as small a flux as 20 C.G.S. lines per ampere turn and per inch of gross length of armature lamination for the coils in the position of minimum inductance. When the conditions conform approximately to any particular case regarding which more definite experimental data is available, this more exact data should, of course, be employed.

The experimental data in the possession of other designers relating to the types with which they are accustomed to deal, may lead them to the

use of numerical values for this constant other than those indicated by the preceding tests; but it will be at once admitted that the chief value of such data lies more in the relative results obtained for various machines, than in the absolute results. The method of applying the constant must hold equally for all types, but doubtless the most suitable value to take for the constant will vary to some extent according to the degree of divergence between the types.

Illustrations of the Calculation of the Reactance Voltage

The determination of the inductance having so important a bearing upon the design, the method will be explained by working out several cases; and when in the following sections several complete working designs

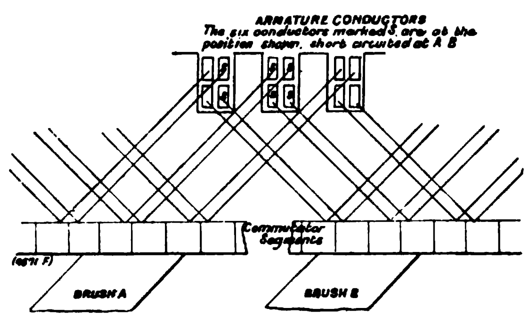


FIG. 174. DIAGRAM ILLUSTRATING INDUCTANCE TESTS

are described, the value of the inductance as related to the general performance of the machine will be considered. All the following cases relate to drum windings:

Case I.—In a four-pole continuous-current dynamo for 200 kilowatts output at 550 volts, and a speed of 750 revolutions per minute, the armature is built with a four-circuit single-winding, arranged in 120 slots, with four conductors per slot. The commutator has a diameter of 20 in., and has 240 segments.

The brushes are .75 in. thick. The segments are .26 in. wide; consequently, as there is one complete turn per segment, three complete turns is the maximum number undergoing short circuit at one brush at any instant.

Considering a group of adjoining conductors in the slots occupying the commutating zone between two pole-tips, six of these conductors, occupying one and one-half slots will be short-circuited, three at one set of brushes

and three at another, as shown digrammatically in Fig. 174. Now the full-load current of this machine is $\frac{200,000}{550} = 364$ amperes, the current per circuit being $\frac{364}{4} = 91$ amperes. Consequently, while any one coil is short-circuited under the brush, the current of 91 amperes in one direction must be reduced to zero, and there must be built up in it a current of 91 amperes in the other direction by the time it emerges from the position of short circuit under the brush, to join the other side of the circuit. This change is at times occuring simultaneously in a group of six adjacent conductors.

A coil has an inductance of one henry when it is situated in a medium of such permeability, and is so dimensioned that a current of one ampere sets up a magnetic flux of such magnitude that the product of the number of lines linked with the coil by the number of turns in the coil is equal to 100,000,000. If the coil has but one turn, then its inductance becomes 10^{-8} times the number of lines linked by the turn when one ampere is passing through it. In the case under consideration, the coil is of one turn, but the varying flux linked with it, and hence the voltage induced in it, is proportional not only to the rate of change of its own current, but to the rate of change of the currents in the adjacent turns simultaneously undergoing commutation at different sets of brushes, and at different points of the surface of the same brushes. In this case five other turns are concerned in determining this varying flux, hence the voltage induced will be six times as great as if the coil had alone been undergoing commutation at the moment. It will not be the *square* of six times as great, since it is the voltage in the one turn that it is required to determine.

Had the six turns *in series* belonged to the one coil undergoing commutation, then the induced voltage would have been the *square* of six times as great as for a one-turn coil.

Gross length of lamination = 10 in.

Flux set up in one turn, per ampere in that turn and per inch of length of armature lamination = 20 C.G.S. lines.

Hence flux of self-inductance = 10 × 20 = 200 lines.

Self-inductance = 200 × 10^{-8} = .0000020 henrys.

Mutual inductance of one turn with relation to the six turns simultaneously undergoing commutation = 6 × .0000020 = .000012 henrys.

Circumference of commutator = 20 × π = 62.8 in.

Revolutions per second = $750 \div 60 = 12.5$.
Peripheral speed of commutator = $62.8 \times 12.5 = 785$ in. per second.
Thickness of radial carbon brush = .75 in.
Current is completely reversed in $\frac{.75}{785} = .00095$ seconds, which is the time of completion of a half-cycle. Consequently, the reversal occurs at an average rate of $\frac{1}{2 \times .00095}$ = 530 cycles per second.

We are now prepared to obtain the reactance of the turn, and shall, for want of a better, make the—in this case—very unwarranted assumption of a sine wave rate of variation:

Reactance = $2 \times \pi \times 530 \times .000012 = .040$ ohms.
Reactance voltage = $91 \times .040 = 3.6$ volts.

This is the voltage estimated to be induced in the turn during the process of commutation. In each of the other five turns independently undergoing commutation under other sets of brushes, and under other parts of the bearing surface of the same set of brushes, there is also an induced voltage of 3.5 volts.

In this design, the factors most concerned in the process of commutation are the following:

Reactance voltage of short-circuited coil	3.6 volts
Inductance per commutator segment...	.000012 henrys
Armature ampere turns per pole-piece	5500 ampere turns
Current per armature circuit	91 amperes
Average voltage per commutator segment	9.2 volts

Case II.—A six-pole continuous-current dynamo has a rated output of 200 kilowatts at 600 revolutions per minute and 500 volts.

The armature has a six-circuit winding, arranged in 126 slots, with eight conductors per slot. The commutator has 252 segments. There are two turns in series per segment. The diameter of the commutator is 20 in. and the width of a segment is .24 in. The thickness of the radial bearing carbon brushes is .63 in., consequently the maximum number of coils short-circuited at any time at one set of brushes is three. Hence $3 \times 2 \times 2 = 12$ conductors grouped together in the neutral zone between two pole tips, and occupying one and one-half slots, are simultaneously undergoing commutation, that is, six conductors at one set of brushes and the other six at the next set.

Gross length of lamination = 9 in.

Flux set up in 12 turns by 1 ampere in those turns, and with 9 in. length of armature lamination $= 12 \times 20 \times 9 = 2160$ C.G.S. lines. Mutual inductance of one coil (two turns) with relation to the six coils simultaneously undergoing commutation $= 2160 \times 10^{-8} \times 2 = .0000432$ henrys.

Circumference of commutator = 62.8 in.
Revolutions per second $= 600 \div 60 = 10$.
Peripheral speed commutator $= 62.8 \times 10 = 628$ in. per second.
Thickness of radial bearing carbon brush = .63 in.

Current completely reversed in $\frac{.63}{628} = .0010$ seconds.

Average rate of reversal $= \frac{1}{2 \times .0010} = 500$ cycles per second.

Reactance $= 2 \times \pi \times 500 \times .0000432 = .136$ ohms.

Amperes per armature circuit $= \frac{200,000}{500 \times 6} = 66.7$ amperes.

Reaction voltage $= 66.7 \times .136 = 9.1$ volts.

(This, of course, is an undesirably high figure, and would only be permissible in connection with especially good constants in other respects.)

Reactance voltage of short-circuited coil	9.1 volts
Inductance per commutator segment...	.000043 henrys
Armature ampere turns per pole-piece	5600 ampere turns
Current per armature circuit	67 amperes
Average voltage per commutator segment	12 volts

Case III.—A 10-pole lightning generator has a rated output of 300 kilowatts at 125 volts and 100 revolutions per minute. It has a 10-circuit, single-winding, arranged, four conductors per slot, in 180 slots. The commutator has 360 segments, one segment per turn. Diameter of commutator is 52 in., and the width of a segment is .45 in.

The thickness of the radial bearing carbon brushes is 1 in., and the maximum number of coils short-circuited at any time at one set of brushes is three. Hence six conductors, grouped together at the neutral zone between any two pole tips, are concerned simultaneously in the commutating process.

Gross length of lamination = 17.6 in.

Flux set up in six turns by one ampere in each of them, and with 17.6 in. length of armature lamination $= 6 \times 20 \times 17.6 = 2110$ C.G.S. lines.

Mutual inductance of one coil of one turn, with relation to the six coils simultaneously undergoing commutation $= 2110 \times 10^{-8} \times 1 = .0000211$ henrys.

Circumference of commutator $= 52 \times \pi = 164$ in.
Revolutions per second $= 100 \div 60 = 1.67$ revolutions.
Peripheral speed commutator $= 164 \times 1.67 = 274$ in. per second.
Thickness of radial bearing carbon brush $= 1$ in.

Current completely reversed in $\frac{1}{274} = .03365$ seconds.

Average rate of reversal $= \frac{1}{2 \times .00365} = 137$ cycles per second.

Reactance $= 2 \times \pi \times 137 \times .0000211 = .018$ ohms.

Rated full load current output $= \frac{300{,}000}{125} = 2400$ amperes.

Current per armature conductor $= \frac{2400}{10} = 240$ amperes.

Reactance voltage $= 240 \times .018 = 4.3$ volts.

Reactance voltage of short-circuited coil	4.3 volts
Inductance per commutator segment	.000021 henrys
Armature ampere turns per pole-piece	8600 ampere turns
Current per armature circuit	240 amperes
Average voltage per commutator segment	3.5 volts

MODERN CONSTANT POTENTIAL COMMUTATING DYNAMOS

Direct-Connected, 12-Pole, 1500-Kilowatt, 600-Volt Railway Generator. Speed = 75 Revolutions per Minute.—This machine is remarkable in that at the time it was designed no commutating dynamo of more than a fraction of its capacity had been constructed. Owing to the great weight of the various parts, and the short time in which the machine had to be constructed, it was assembled and tested for the first time at the Columbian Exposition.

It was found that the machine complied with the specification in all particulars as to heating, and that sparking did not occur between the limits of no-load and 50 per cent. overload. Mention is made of this, since this was the first of the modern traction generators developed in the United States; and the constants of this machine, which were novel at that time, have since become common in the best practice in designing. Perhaps the most remarkable feature of this machine is the range of load at which sparkless commutation occurs, and the great magnetic strength of the armature as compared with that of the field-magnets. This result

was accomplished, first, by comparatively low inductance of the armature coils; secondly, high magnetisation in the armature projections, which to some extent keeps down distortion of the magnetic field; and, thirdly, by the over-compounding of the machines to suit railway practice: that is, no-load volts of 550 and full-load volts of 600. The increase of magnetisation corresponding to this increase of voltage is a condition favourable to sparkless commutation; and it will be noted from the particulars given of the machine that the magnetising force of the series coil at full load is approximately equal to that of the shunt coil at no load.

Drawings are given, Figs. 175 to 177, pages 196, 198, and 200, showing the construction; Figs. 178 and 179, page 203, show saturation and compounding curves for this machine. The following specification sets forth its constants and the steps in the calculations.

SPECIFICATION OF 12-POLE, 1500-KILOWATT, 600-VOLT GENERATOR, FOR SPEED OF 75 REVOLUTIONS PER MINUTE

Number of poles	12
Kilowatts	1500
Revolutions per minute	75
Frequency in cycles per second	7.5
Terminal volts, no load	550
„ „ full load	600
Amperes, full load	2500

DIMENSIONS

Armature:

Diameter over all	126 in.
Length over conductors	$48\frac{1}{4}$ „
Diameter at bottom of slots	$121\frac{3}{4}$ „
Internal diameter of core	$103\frac{3}{4}$ „
Length of core over all	$33\frac{3}{4}$ „
Effective length, magnetic iron	26.8
Pitch at surface	33 in.
Insulation between sheets	10 per cent.
Thickness of sheets	.014 in.
Depth of slot	$2\frac{1}{8}$ „
Width of slot at root	$\frac{11}{16}$ „
„ „ surface	$\frac{3}{8}$ „
Number of slots	348
Minimum width of tooth	.412 in.
Width of tooth at armature face	.763 „
„ conductor	$\frac{7}{32}$ „
Depth of „	$\frac{3}{4}$ „

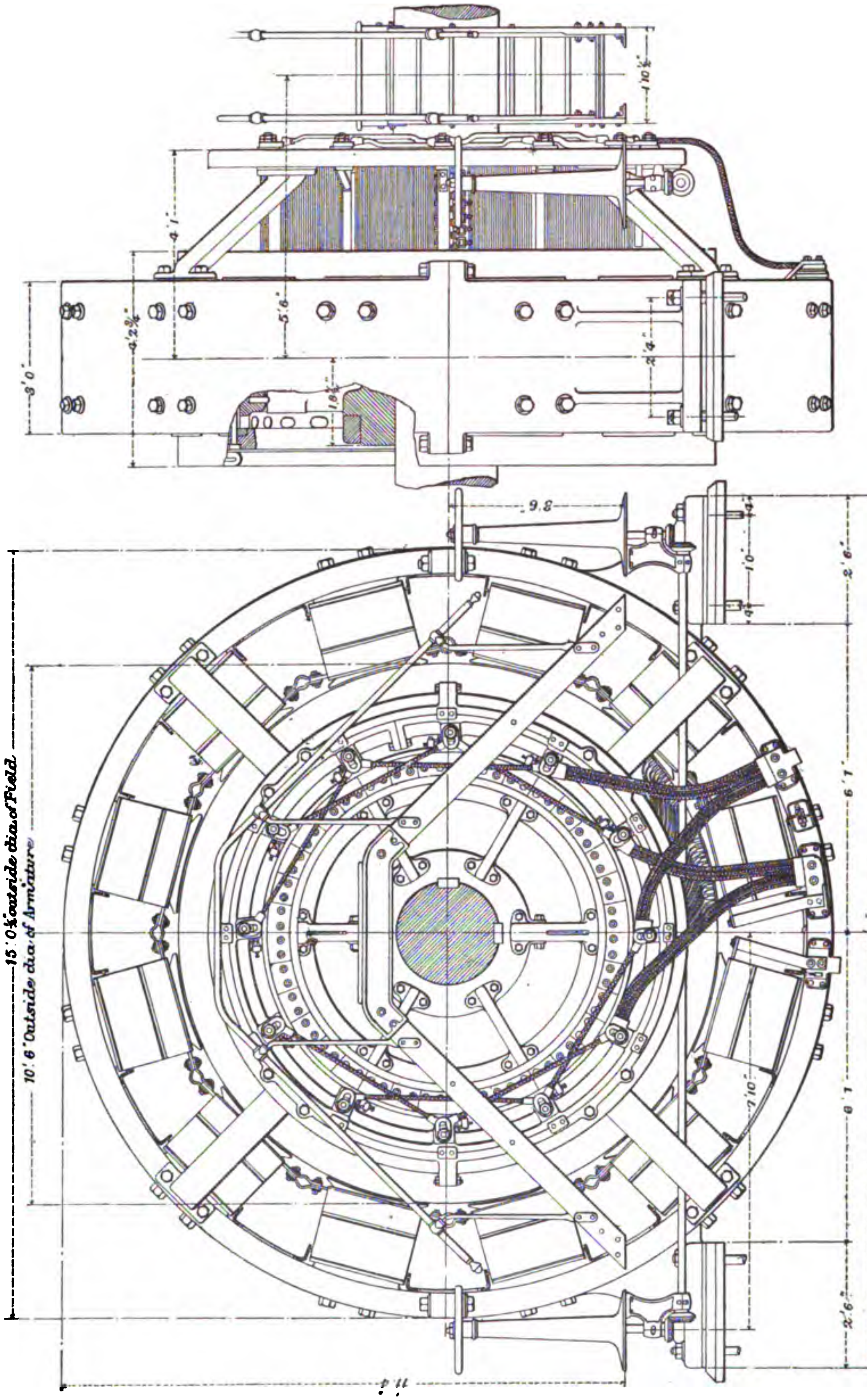


FIG. 175. 12-POLE, 1500-KILOWATT, 600-VOLT RAILWAY GENERATOR

Number of ventilating ducts	8
Width of each ventilating duct	$\frac{1}{2}$ in.
Effective length of core ÷ total length	.795

Magnet Core:

Length of pole-face	$33\frac{3}{4}$ in.
" pole arc	$24\frac{1}{4}$ "
Pole arc ÷ pitch	.73
Thickness of pole-piece at edge of core	$1\frac{9}{16}$ in.
Radial length of magnet core	18 "
Width of magnet core	14 "
Thickness of magnet core	30 "
Diameter of bore of field	$126\frac{7}{8}$ "
Depth of air gap	$\frac{7}{16}$ "

Spool:

Length over flanges	$17\frac{7}{8}$ in.
" of winding space	$16\frac{7}{8}$ "
Depth " "	$3\frac{7}{8}$ "

Yoke:

Outside diameter	$190\frac{1}{2}$ in. and $180\frac{1}{2}$ in.
Inside	168 in.
Thickness, body	$6\frac{1}{4}$ "
Length along armature	36 "

Commutator:

Diameter	$86\frac{1}{2}$ in.
Number of segments	696
" " per slot	2
Width of segment at commutator face	.342 "
" " root	.313 "
Depth of segment	3 "
Thickness of mica insulation	.05 "
Available length of surface of segment	$88\frac{7}{8}$ "
Cross-section of commutator leads	.130 square inches

Brushes:

Number of sets	12
" in one set	6
Width	2.5
Thickness	.75
Area of contact of one brush	1.875
Type of brush	Radial carbon

MATERIALS

Armature core	Sheet iron
" spider	Cast iron
Conductors	Copper

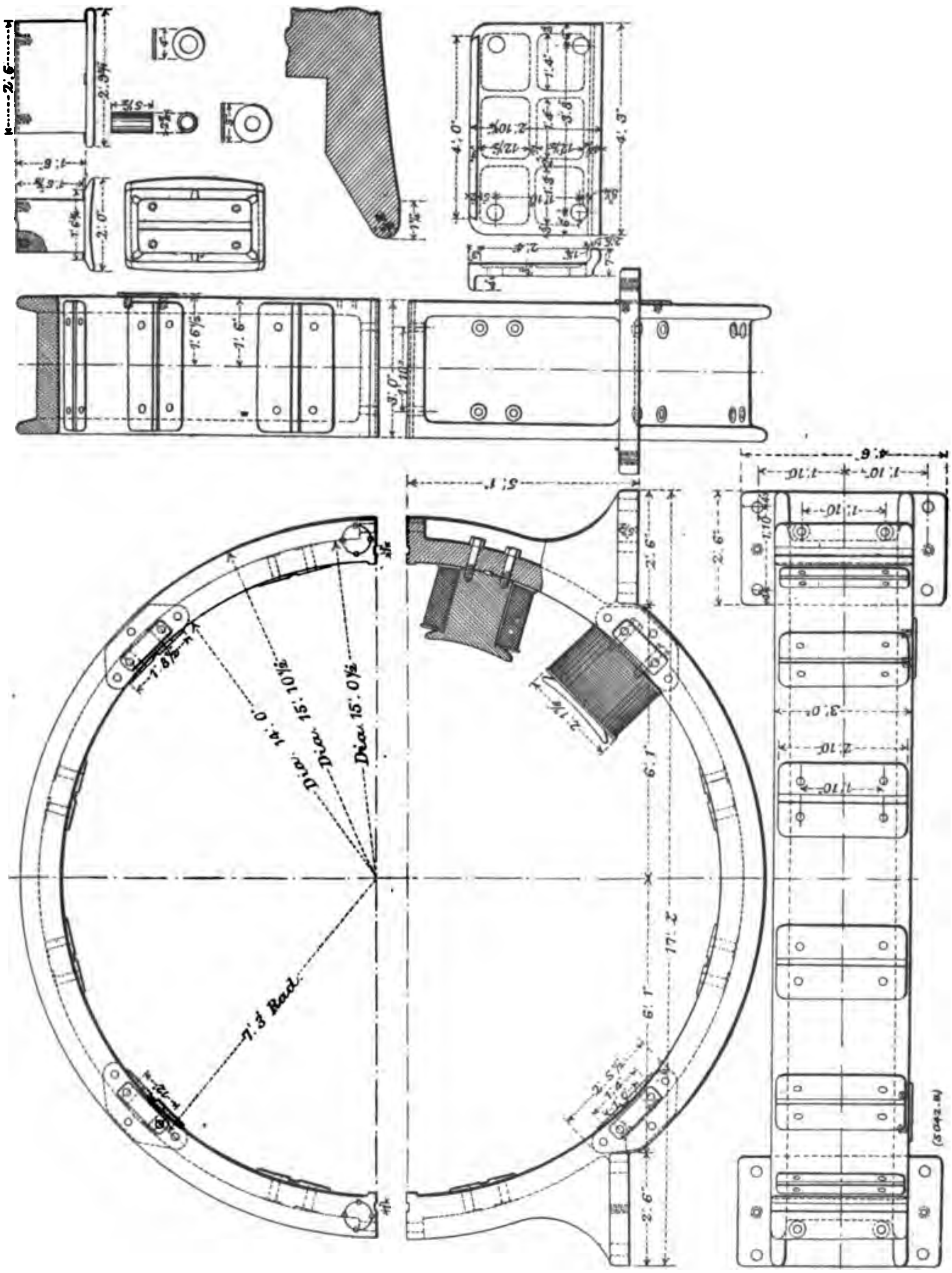


FIG. 176. 12-POLE, 1500-KILOWATT, 600-VOLT RAILWAY GENERATOR

Commutator segments	Copper
" leads...	German silver
Spider	Cast iron
Pole piece	Cast steel
Yoke	"
Magnet core	"
Brushes	Carbon

TECHNICAL DATA

Armature, no load voltage	550
Number of face conductors	1392
Conductors per slot	4
Number of circuits	12
Style of winding	Single
Gramme ring or drum	Drum
Type construction of winding	Evolute end connections
Mean length one armature turn	176 in.
Total armature turns	696
Turns in series between brushes	58
Length between brushes	10.200 in.
Cross-section, one armature conductor	.161
Ohms per cubic inch at 20 deg. Cent.	.00000068 ohms.
Resistance between brushes at 20 deg. Cent.	.043 "
" " 60 "	.050 "
Volts drop in armature at 60 deg. Cent.	10.3
" brush contact	2.5
" series winding	1.9
Terminal voltage, full load	600
Total internal voltage, full load	620
Amperes per square inch in armature winding	1290
" " commutator segments	3200

Commutation :

Average voltage between commutator segments	10.3
Armature turns per pole	58
Amperes per turn	208
Armature ampere turns per pole	12,100
Segments lead of brushes	$6\frac{1}{4}$
Percentage lead of brushes	10.8
" demagnetizing ampere turns...	21.6
" distorting ampere turns	78.4
Demagnetizing ampere turns per pole	2610
Distorting " "	9490
Frequency of commutation (cycles per second)	227
Number of coils simultaneously short-circuited per brush ...	2
Turns per coil	1
Number of conductors per group simultaneously undergoing commutation	4

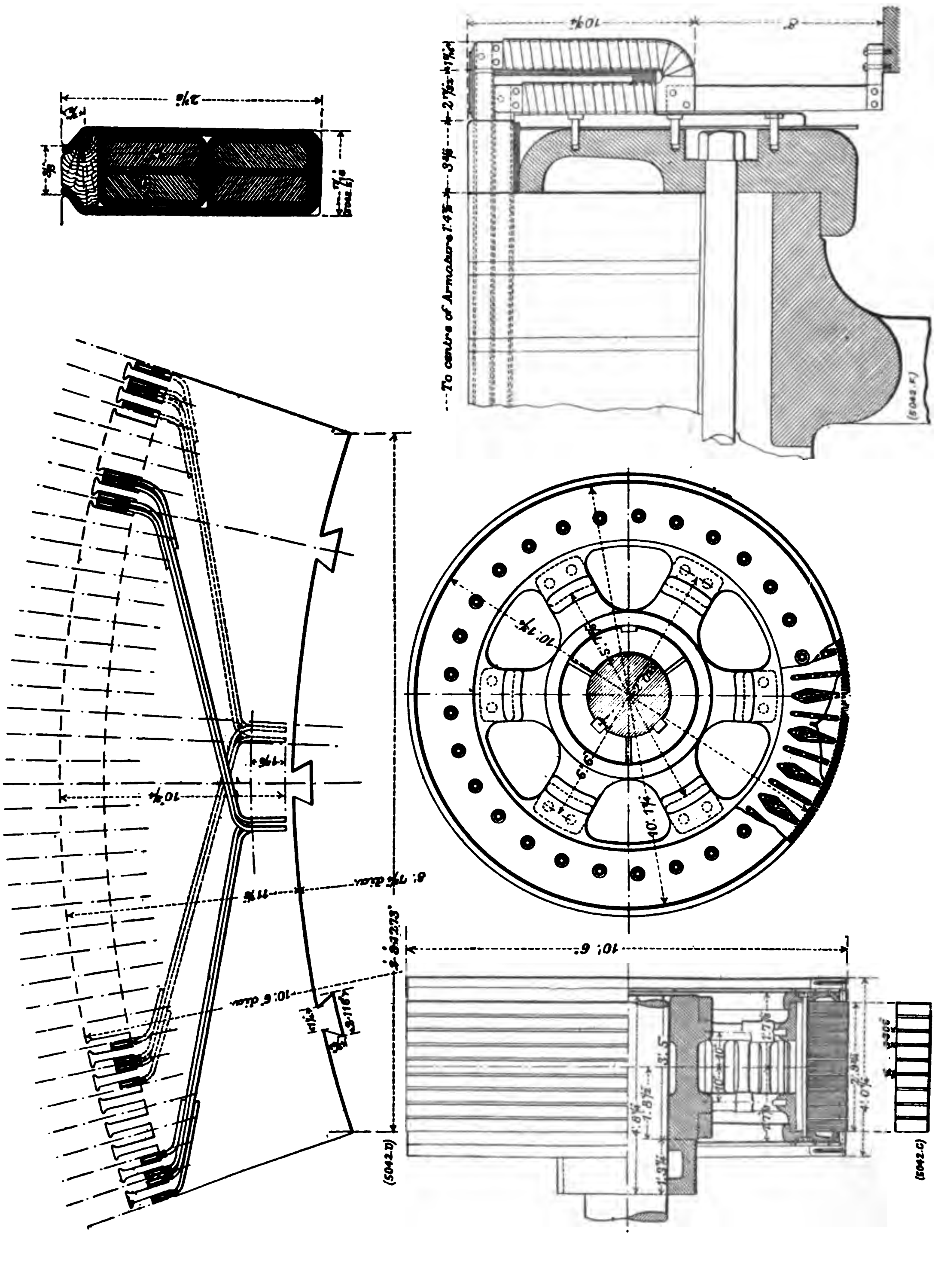


FIG. 177. DETAILS OF 12-POLE, 1500-KILOWATT, 600-VOLT RAILWAY GENERATOR

Flux per ampere turn per inch length armature lamination ...	20 (assumed)
„ linked with four turns = 36.7 × 20 × 4	2700
Inductance in one turn constituting one coil, in henrys = $1 \times 2700 \times 10^{-8}$	.000027
Reactance short-circuited turn	.0385 ohms
„ voltage = .0385 × 208	8.0 volts

In operating these machines, the brushes are set at a constant lead of $6\frac{1}{4}$ segments for all loads, and the output may temporarily exceed the full load rated output by 50 per cent.

MAGNETIC DATA

Coefficient of magnetic leakage	1.15
Megalines entering armature per pole-piece at no load and 550 volts	31.6
Megalines entering armature per pole-piece at full load and 620 inter. volts	35.6
Armature :	
Section	241 square inches
Length (magnetic)	19 in.
Density at no load	66 kilols.
„ at full load	74 „
Ampere turns per inch length no load	15
„ „ full load	18
„ no load	·290
„ full load	340
Teeth :	
Transmitting flux from one pole-piece	.24
Section at roots	264 square inches
Length	2.125 in.
Apparent density at no load	120 kilols.
„ „ full load	135 „
Corrected density at no load	116 „
„ „ full load	126 „
Ampere turns per inch length, no load	1800
„ „ full load	1400
„ no load	1700
„ full load	3000
Gap :	
Section at pole face	820 square inches
Length gap	.43 in.
Density at pole face, no load	32 kilols.
„ „ full load	44 „
Ampere turns, no load	5300
„ full load	6000

Magnet Core:

Section	420 square inches
Length (magnetic)	20 in.
Density, no load	87 kilols.
„ full load	98 „
Ampere turns per inch length, no load	67
„ „ full load	160
„ no load	1350
„ full load	3200

Magnet Yoke:

Section	225 square inches
Length per pole	27 in.
Density, no load	81 kilols.
„ full load	91 „
Ampere turns per inch length, no load	49
„ „ full load	110
„ no load	1320
„ full load	3000

Ampere Turns per Spool

	No Load and 550 Volts.	No Load and 620 Internal Volts.
Armature core	290	340
„ teeth	1700	3000
Air gap	5300	6000
Magnet core	1350	3200
Yoke	1320	3000
	9960	15,540

Demagnetising ampere turns per pole-piece at full load ...	2600
Allowance for increase in density through distortion	1000
Total ampere turns at full load of 2500 amperes and 600 terminal volts	19,140

If the field rheostat is so adjusted that the shunt winding shall supply the 9960 ampere turns necessary for the 550 volts at no load, then, when the terminal voltage has risen to 600 volts at full load, the shunt winding will be supplying $\frac{600}{550} \times 9960 = 10{,}840$ ampere turns. The series winding must, at full load, supply the remaining excitation, *i.e.*, $19{,}140 - 10{,}840 = 8300$ ampere turns. The armature has 1392 face conductors, hence the armature strength expressed in ampere turns per pole piece is, at full load current of 2500 amperes (208 amperes per circuit):

$$\frac{1392}{2 \times 12} \times 208 = 12{,}100 \text{ ampere turns per pole-piece, on armature.}$$

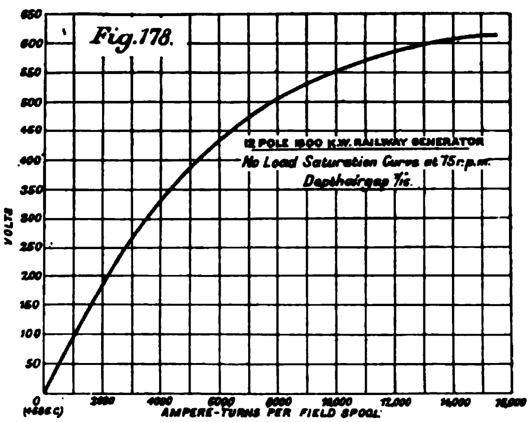
CALCULATION OF SPOOL WINDINGS

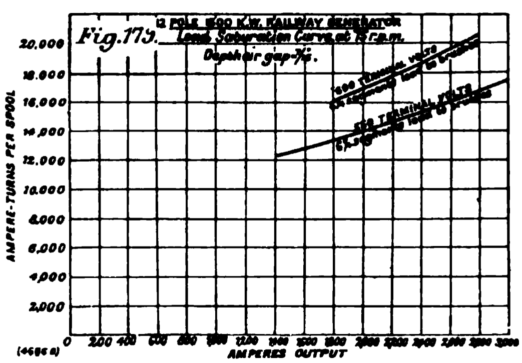
Shunt:

Mean length of one shunt turn	**8.5 ft.**
Ampere turns per shunt at full load	**10,840**
„ feet	**92,000**
Radiating surface one shunt spool	**1130 square inches**
Permit .36 watts per spool at 20 deg. Cent.	
Then shunt watts per spool at 20 deg. Cent.	**405**
And „ „ 60 „	**468**

Pounds copper per coil $= \dfrac{31 \times 92^2}{405} = 650$ **lb.**

A margin of 16.6 per cent. in the shunt rheostat when coils are hot leaves 83 per cent. of the available 600 volts, or 500 volts, at the terminals





FIGS. 178 AND 179. SATURATION AND COMPOUNDING CURVES

of field spools. This is equivalent to 432 volts, or 36 volts per spool, when spools have a temperature of 20 deg. Cent.

Hence require $\dfrac{405}{36} = 11.3$ **amperes in shunt coils.**

Turns per shunt spool $= \dfrac{10{,}800}{11.3}$	**960**
Length of 960 turns	**8150 ft.**
Pounds per 1000 feet	**79.8**

No. 6 B. and S. gauge weighs 79.5 lb. per 1000 feet.
Bare diameter = .162 in. D.C.C.D. = .174 inch.
Cross section = .0206 square inch.
Current density = 546 amperes per square inch
Length of the portion of winding space available for shunt coil = 9.0 inches.
Depth of winding, 3.9 inches.

Series Winding.—**The series winding is required to supply 8300 ampere turns at full load. With 4.5 turns per spool, the full load current**

will give 2500 × 4.5 = 11,250 ampere turns. Consequently, 650 amperes must be diverted through the diverter rheostat, leaving 1850 amperes in the series winding, giving 8300 ampere turns.

The 4.5 turns consist of ten bands in parallel, each 7 in. wide by $\frac{1}{16}$ in. thick.

Cross-section conductors	4.375 square inches
Current density	424 amperes per sq. in.
Resistance of 12 spools at 20 deg. Cent.	.000855 ohms
Series C^2 R at 20 deg. Cent. per spool	244 watts
" " 60 " "	282 "
Weight series copper per spool	650 lb.

ESTIMATED CORE LOSS

Total weight armature laminations	26,000 lb.
Cycles per second	7.5
Kilolines density in core	74.
$\frac{\text{Cycles} \times \text{Density}}{1000}$	.56
Corresponding watt core loss per pound	.9
Total estimated core loss	23,400 watts

THERMAL CALCULATIONS

Armature :

C^2 R loss at 60 deg. Cent.	25,850 watts
Core loss (estimated value)	23,400 "
Total armature loss	49,250 "
Peripheral radiating surface armature	19,100 square inches
Watts per square inch radiating surface armature	2.6 watts
Peripheral speed armature, feet per minute	2480
Rise in temperature at 15 deg. Cent., rise per watt per square inch...	39 deg. Cent.

Spool :

Total C^2 R loss at 60 deg. Cent., per spool	750 watts
Peripheral radiating surface, one spool	2080 square inches
Watts per square inch of radiating surface, warm	.41 watts
At 80 deg. Cent. rise per watt per square inch, rise in temperature of field spool is	33 deg. Cent.

Commutator :

Area bearing surface all positive brushes	67.5 square inches
Amperes per square inch of brush bearing surface	37 amperes
Ohms per square inch bearing surface of carbon brush ...	.03 ohm
Brush resistance, positive + negative...	.00089 ohm
Volts drop at brush contacts	2.22 volts
C^2 R at brush contacts	5550 watts
Brush pressure	1.25 lb.

Coefficient of friction	.3
Peripheral speed of commutator in feet per minute	1700
Brush friction	1040 watts
Stray power loss in commutator	750 „
Total commutator loss	7340 „
Radiating surface commutator...	5400 square inches
Watts per square inch of radiating surface	1.36 watts
Rise in temperature at 20 deg. Cent. rise per watt per square inch...	27 deg. Cent.

EFFICIENCY CALCULATIONS

	Watts.
Output at full load	1,500,000
Core loss (estimated)	23,400
C^2 R armature at 60 deg. Cent.	25,850
Commutator and brush loss	5,550
Shunt spools C^2 R at 60 deg. Cent.	5,650
„ rheostat „ „	1,130
Series spools – C^2 R at 60 deg. Cent.	3,380
„ rheostat „ „	1,190
Total input	1,566,150

Commercial efficiency at full load and 60 deg. Cent. = 95.7 per cent.

WEIGHTS (POUNDS)

Armature:	
Magnetic core	24,000
Teeth	2,420
Copper	6,360
Commutator, segments	3,100
Twelve magnet cores and pole-pieces	30,000
Yoke	35,000
Twelve shunt coils	7,800
„ series coils	7,800
Total spool copper	15,600

10-POLE, 550-KILOWATT RAILWAY GENERATOR

This machine was designed by Mr. H. F. Parshall, and a number have been used in leading installations with satisfactory results. Figs. 180 and 181, Plates II. and III., illustrate one of a number of these sets as installed at the King's End power-house of the Dublin United Tramways Company. Figs. 182 and 183, page 206, show the principal dimension of the machine. From the results of tests made by the authors, the curves given in Figs. 184 to 188, on page 207, have been derived.

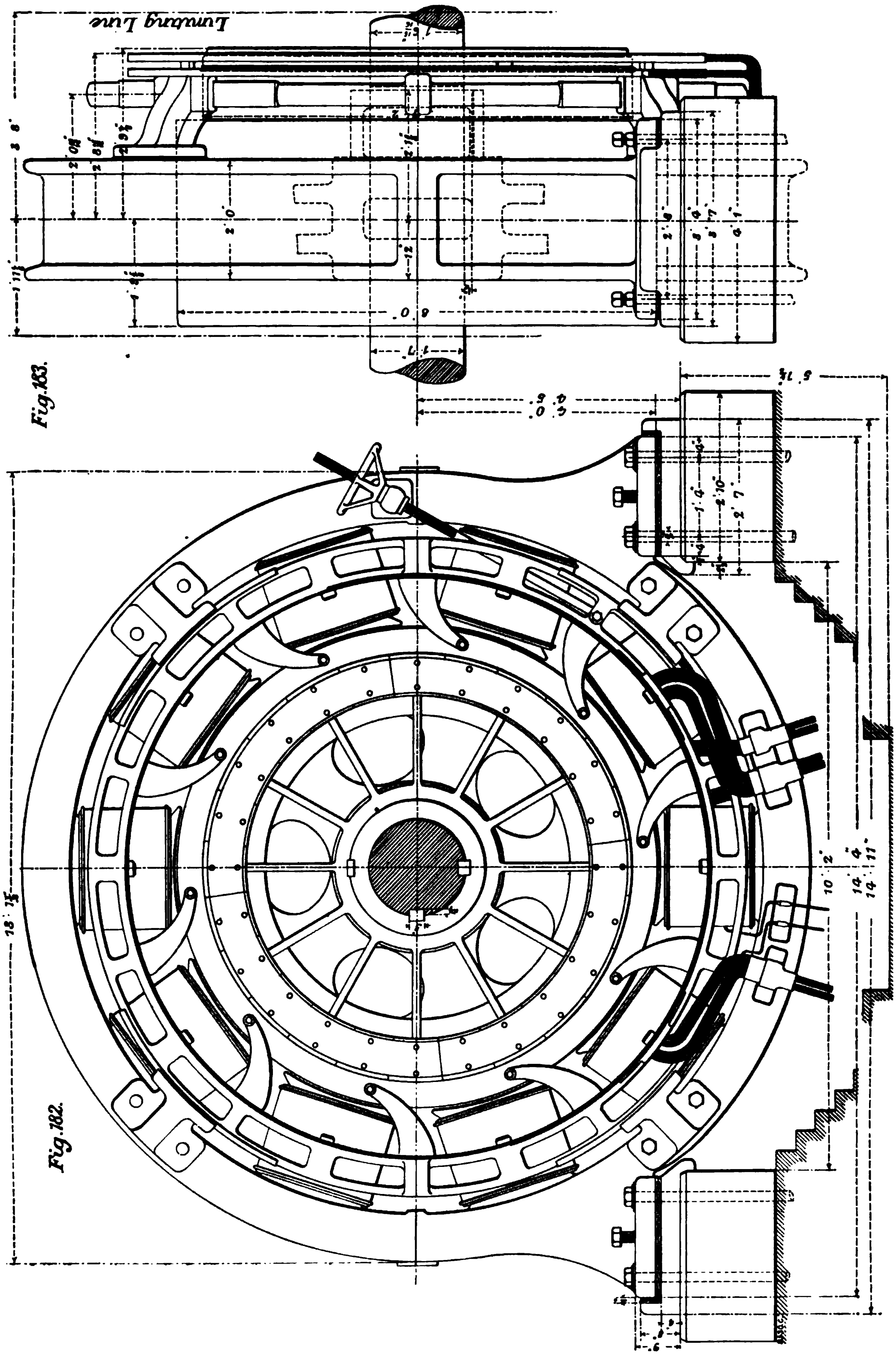
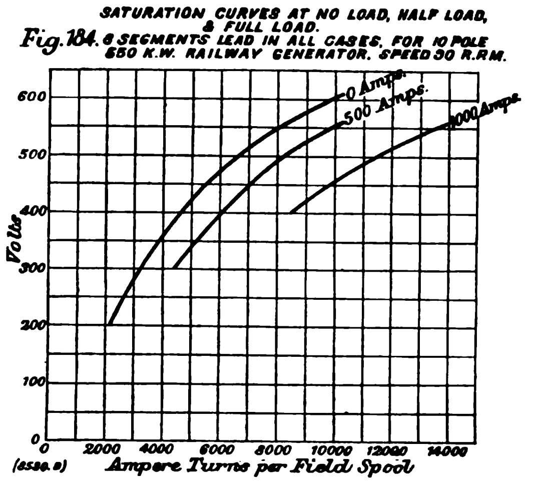
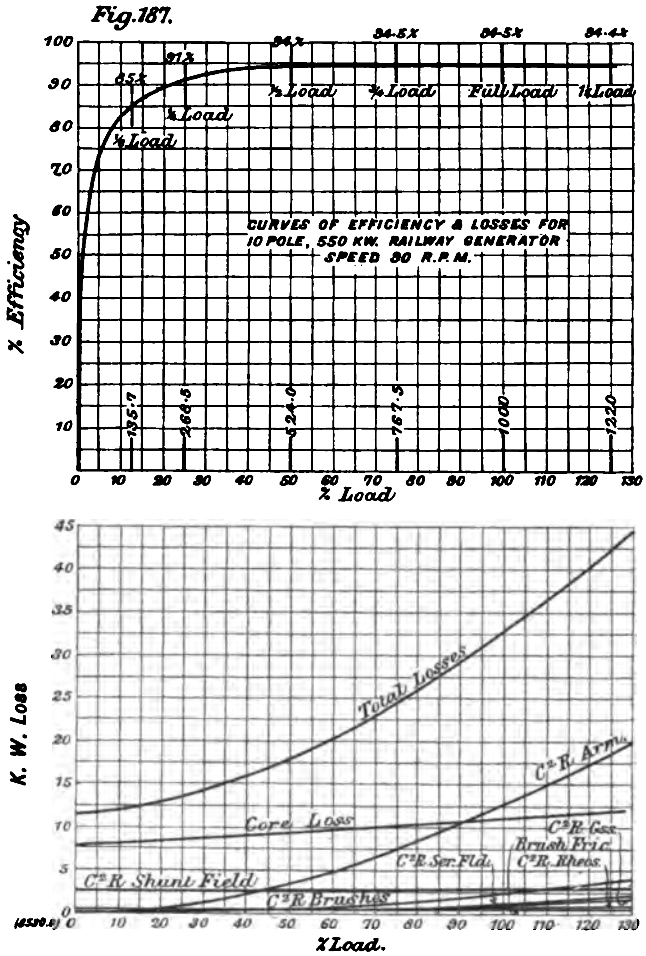


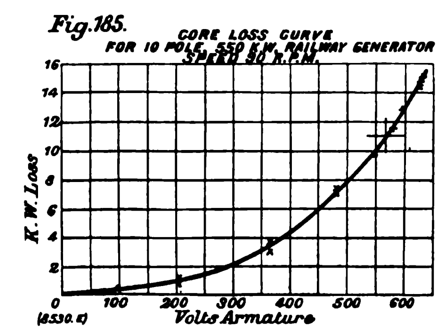
Fig. 183.

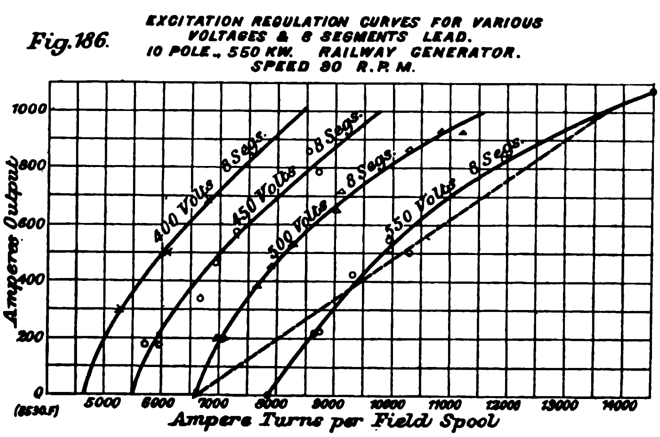
Fig. 182.

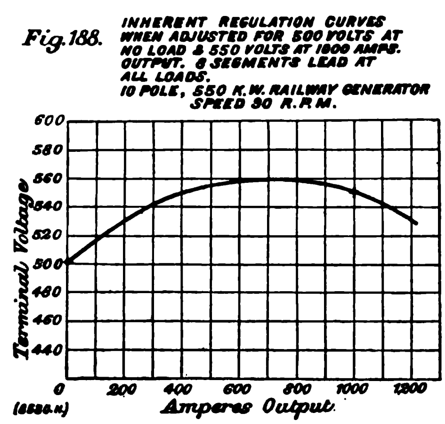
Figs. 182 and 183. 10-Pole, 550-Kilowatt Railway Generator; Speed, 90 Revolutions











FIGS. 184 TO 188. CURVES OF 10-POLE, 550-KILOWATT RAILWAY GENERATOR

SPECIFICATION

Number of poles	10
Kilowatts	550
Revolutions per minute	90
Terminal volts full load	550
,, ,, no load	500
Amperes	1000

DIMENSIONS IN INCHES

Armature:

External diameter	96
Internal diameter	71
Length over conductors	39.4
Gross length of core	20.5
Percentage insulation between laminations	12.5
Effective length of armature core	14.9
Number of ventilating ducts	8
Width of each duct	.437
Thickness of laminations	.014
Pole pitch at armature surface	30.2
Number of slots	300
Slot pitch at surface	1.0
Width of slot	.525
Depth ,,	2
Width of tooth at surface	.475
,, ,, root (minimum)	.436

Bar-winding:

Conductor uninsulated	0.08 × 0.8
Conductors per slot	6
Cross-section of slot, square inches	1.05
,, ,, copper per slot	0.384
Space factor of slot	.365

Magnet Core:

Length of pole face parallel to shaft	18.5
,, ,, arc	23.5
Pole pitch	30.2
,, arc ÷ pole pitch	.78
Radial length of magnet core	18
Diameter of magnet core	18.5
,, bore at pole face	96.75
Depth of air gap	.375

Spool:

Length over flanges	18
,, of winding space	15.875
Depth ,, ,,	2
Available length for shunt spool	8.5
,, ,, for series	7.375

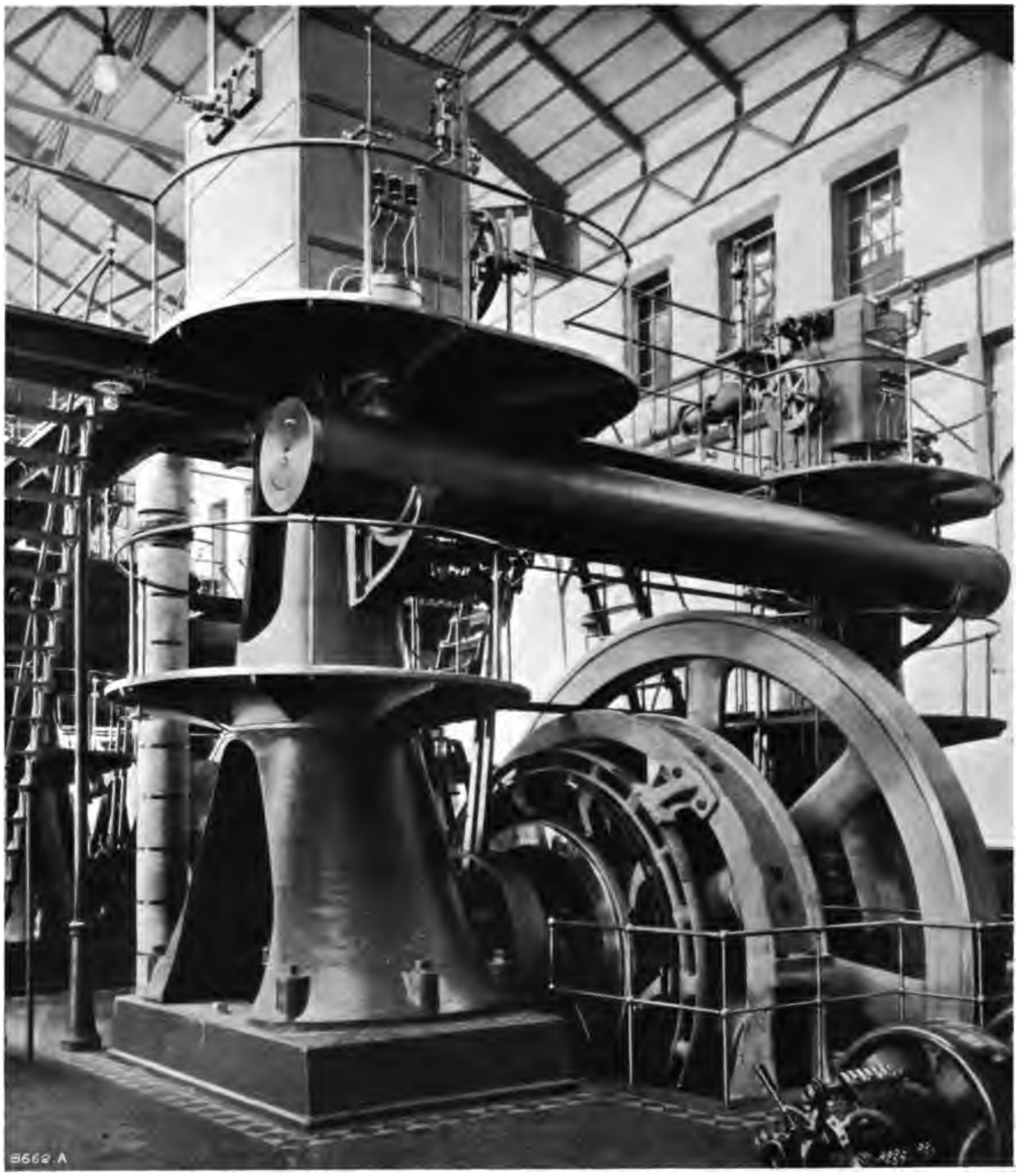
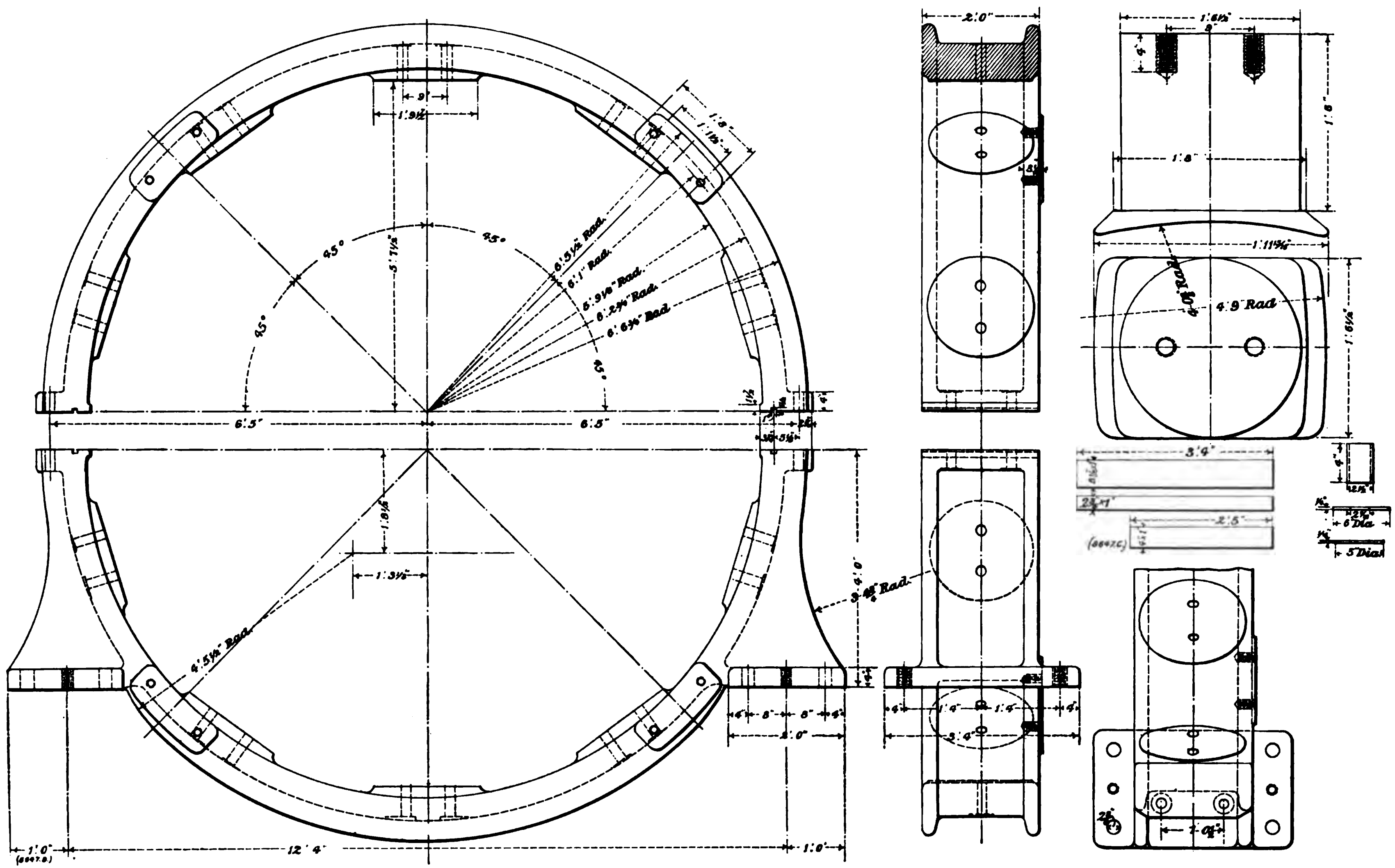
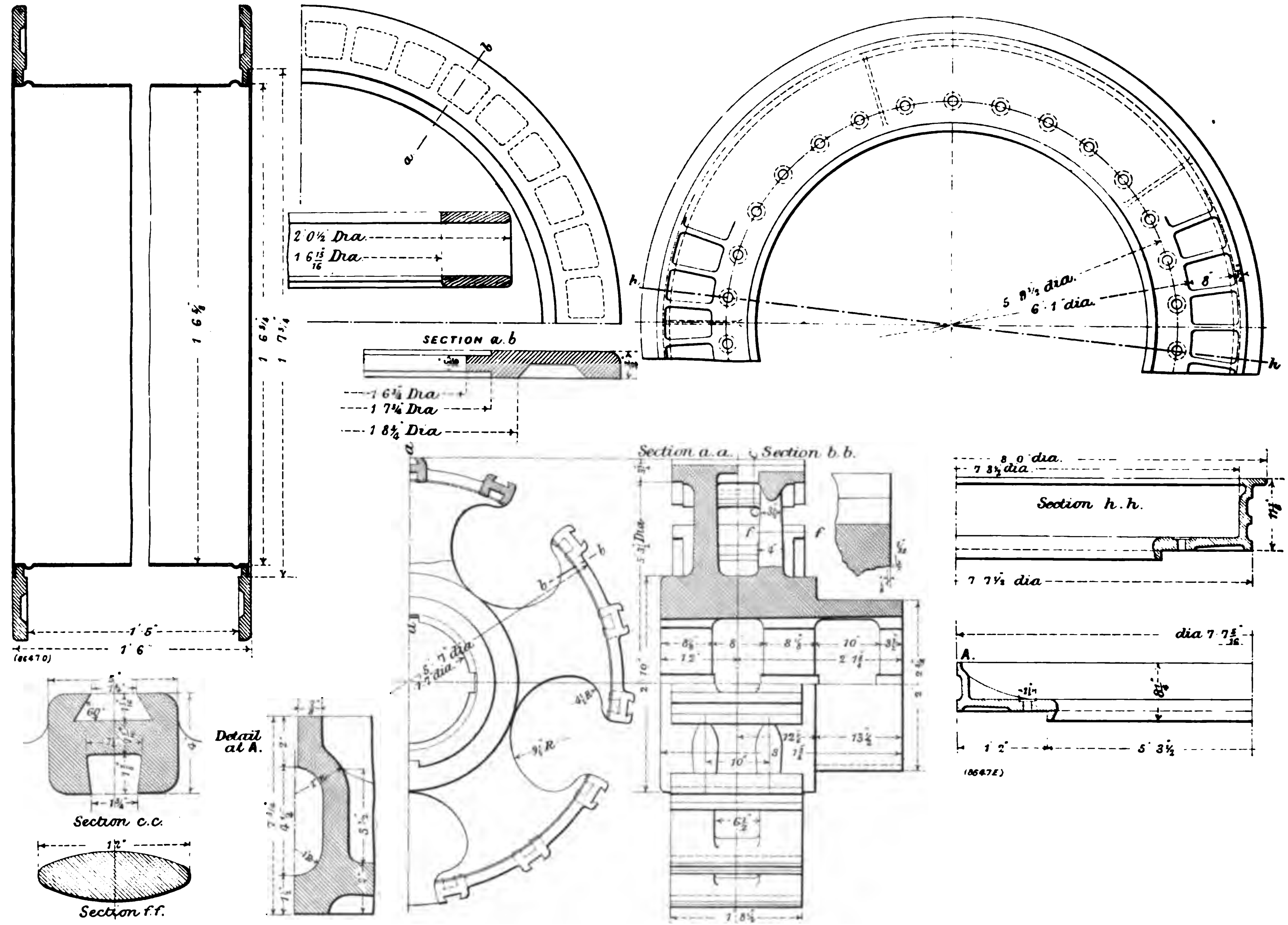


FIG. 180. 10-POLE, 550-KILOWATT, 550-VOLT RAILWAY GENERATOR; SPEED, 90 REVOLUTIONS. DUBLIN



10-Pole, 550-Kilowatt Railway Generator. Magnet Frame and Magnet



10-Pole, 550-Kilowatt Railway Generator. Details of Armature Construction

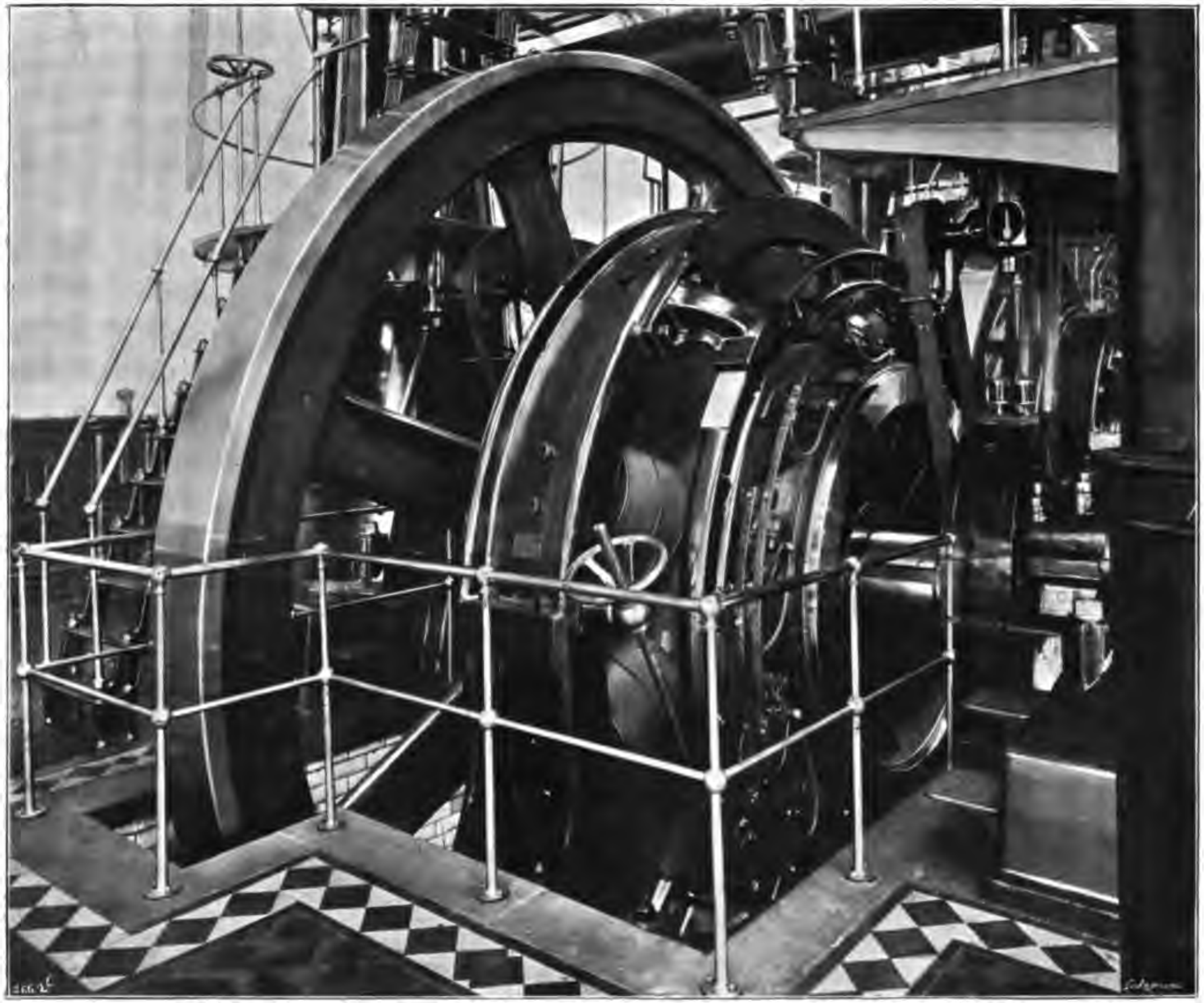
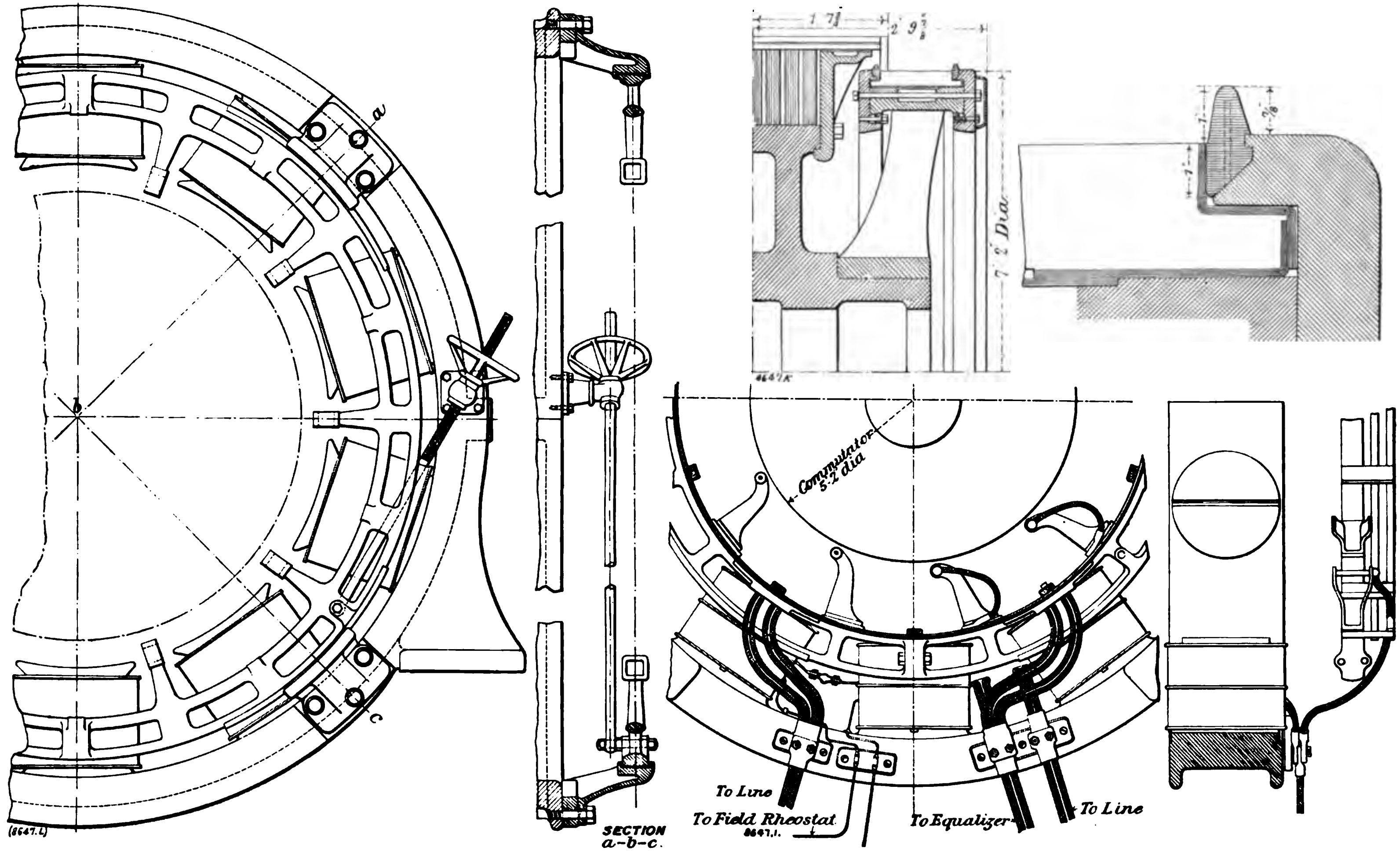


Fig. 181. 10-Pole, 550-Kilowatt, 550-Volt Railway Generator; Speed, 90 Revolutions. Dublin



10-Pole, 550-Kilowatt Railway Generator. Details of General Arrangement

Yoke:

Internal diameter	138.25
Diameter over ribs	157.5
Thickness of yoke, exclusive of ribs	5.625
Length parallel to shaft	24

Commutator:

Diameter	86.5
Number of segments	900
„ „ per slot	3
Width of segment plus insulation at surface	0.302
Thickness of mica insulation	0.05
Width of segment at surface	0.252
Available length of commutator face	8.875
Size of commutator leads	1.0 × .0625

Equalisers:

Number of rings	10
Equaliser points per ring	5

Brushes:

Number of sets	10
„ per set	5
Width of brushes	1.25
Length of arc of contact of brushes	0.8
Area of contact per brush, square inches	1.00
„ „ of all positive brushes	25
Type of brush	Carbon

MATERIALS

Armature core	Sheet iron
„ spider	Cast iron
„ conductors	Copper
Commutator segments	„
„ leads	„
„ spider	Cast iron
Pole shoes	Cast steel
Yoke	„
Magnet cores	„

TECHNICAL DATA

Armature:

No load voltage	500
Full load voltage	550
Style of winding	10 circuit single
Gramme ring or drum	Drum
Number of paths through winding	10
„ conductors per slot	6

Arrangement in slot	3 × 2 deep
Amperes per square inch in armature conductors	1560
Total number of face conductors	1800
„ „ turns	900
Mean length of one turn	113
Cross-section of one conductor, square inches	0.064
Specific resistance of copper at 60 deg. Cent.	0.0008
Resistance of armature at 60 deg. Cent.	0.0127
Volts drop in armature at full load, 60 deg. Cent.	12.7
„ „ brush contacts	2.4
„ „ series winding	2.6
Total volts drop	18
Internal volts at full load	568

Commutator (Sparking Constants):

Width of one segment plus insulation	0.302
Arc of contact	0.8
Number of turns short-circuited	3
Turns per segment	1
$6 \times 20 \times 20.5 =$	2460 C.G.S. lines
$2460 \times 10^{-8} \times 1 =$ inductance in henrys	0.0000246
Circumference of commutator	272
Revolutions per second	1.5
Peripheral speed, inches per second	410
Current completely reversed in $\left(\frac{.8}{410}\right) =$	0.00195 seconds
Frequency of commutation $\left(\frac{1}{2 \times .00195}\right) =$	257
Reactance $= 2\pi\, 257 \times .0000246$	0.039
Current per conductor $\frac{1000}{10} =$	100
Reactance voltage $= 100 \times .039$	3.9

Magnetic Calculations

Megalines entering armature core per pole at no load	18.5
„ „ „ „ „ full load	21.5
Coefficient of magnetic leakage	1.125
Megalines in magnet core, no load	20.8
„ „ „ full load	23.6

Armature:

Cross-section in square inches	312
Density at no load	59,000
„ full load	67,000
Magnetic length	12.8
Ampere-turns per inch length at no load	16.0
„ „ full load	27.0
„ for armature at no load	204
„ „ full load	345

Teeth :

Ratio of polar arc to pole pitch	0.78
Total number of teeth	300
Number of teeth per pole (taking 5 per cent. for spread)	
$= \frac{300}{10} \times .78 \times 1.05 =$	24.5
Cross-section teeth at root	160
Apparent density at no load	116,000
„ „ full load	131,000
Mean width of tooth ÷ width of slot	0.88
Corrected density, no load	114,000
„ „ full load	124,000
Magnetic length	2
Ampere turns per inch, no load	200
„ „ full load	600
„ for teeth, no load	400
„ „ full load	1400

Magnet Core :

Cross-section in square inches	268
Density at no load	78,000
„ full load	88,000
Magnetic length	18
Ampere turns per inch length, no load	35
„ „ full load	70
„ for magnet core at no load	630
„ „ full load	1080

Air Gap :

Cross-section of pole face	430
Density at no load	43,000
„ full load	48,000
Magnetic length	0.375
Ampere turns for air gap, no load	5000
„ „ full load	5700

Yoke :

Cross-section in square inches	300
Density at no load	69,000
„ full load	79,000
Magnetic length	22.5
Ampere turns per inch length at no load	30
„ „ full load	50
„ at no load	670
„ full load	1130

Saturation Ampere Turns per Spool

	No Load.	Full Load.
Armature core	204	345
„ teeth	400	1400
Gap	5000	5700
Magnetic core	630	1080
„ yoke	670	1130
Total ...	6904	9655

Value of ampere turns at no load, 500 volt	6900
„ „ „ 568 internal voltage	9600
„ „ „ 550 „ „	8800
Ampere turns to overcome ohmic drop	800

Armature Interference:

Armature turns per pole	90
Amperes per circuit	100
Ampere turns per pole	9000
Segments lead of brushes	8
Percentage	9
Apparent tooth density, full load	131,000
Field ampere turns at no load, 550 volt (K)	8800
Ampere turns to overcome ohmic drop (H)	800
Demagnetising ampere turns per pole (C.)	1600
Total distorting ampere turns per pole (D)	7400
Ampere turns for teeth and gap, full load (S)	7100
$D \div S$	1.04
$F \div D$ (from curve of Fig. 149, page 146)	0.23
Field ampere turns to overcome distortion (F)	1700
Total ampere turns full load $(F+G+H+K)$	12,900

Shunt Spool:

External diameter of spool	23.2
Internal „ „	19
Mean length of one turn in inches	66
„ „ feet	5.6
Ampere turns per shunt spool	7750
Ampere feet per spool 7750 × 5.6	43,500
Watts per spool at 20 deg. Cent. $= 31 \times \dfrac{\left(\dfrac{43,500}{1000}\right)^2}{242}$	240
Watts lost in shunt and rheostat	3640
Amperes per shunt spool at 550 volts	6.6
Resistance shunt at 60 deg. Cent.	6.4
„ of 10 spools	64
Length of wire per spool in feet	6600

B. and S. guage No. 9	780 turns		
„ „ No. 10	374 „		
Turns per spool, total	1154		
Bare diameter		0.114 and	0.102
D. C. C. diameter		0.126 „	0.112
Cross-section, square inches		0.0103 „	0.00815
Amperes per square inch		640 „	810

Available winding space for shunt	8.5
Average number of turns per layer	86
Number of layers	17
Watts per spool at 60 deg. Cent.	278
External cylindrical surface for shunt spool, square inches	620

Watts per square inch of external surface	0.45
Weight of shunt copper per spool, pounds	242
" " for all spools	2420

Shunt Rheostat:

Current in rheostat	6.6
Resistance of rheostat	16.8
Watts loss in rheostat	730

Series Spool:

Ampere turns per series spool at 550 volts	5150
Amperes per series spool	600
Amperes diverted	400
Turns per spool	8.5
Size of conductor	.145 × 6.5
Number in parallel	1
Cross-section—square inches...	.95
Current density	630
Mean length of one turn	65
Total length of copper in 10 spools in feet...	460
Resistance of 10 spools at 60 deg. Cent.	0.00435
C R drop in series windings	2.6
Watts lost in series spools at 60 deg. Cent.	1560
Weight of series copper, in pounds	1700

Series Diverter:

Resistance at 60 deg. Cent.	0.0065
Amperes in diverter	400
Watts lsot in "	1040
" series spool	1560
Total watts lost in series windings	2600

THERMAL CALCULATIONS.

Armature:

Current in armature	1000
Resistance of " 60 deg. Cent.	0.0127
Watts lost in " 60 "	12,700
Density in core, full load	67,000
Cycles per second	7.5
$\frac{\text{Density} \times \text{cycles per second}}{1000}$	500
Watts per pound, from core loss curve	1.02
Weight of core laminations—pounds	10,800
Watts iron loss	11,000
Total loss in armature	23,700
Peripheral radiating surface of armature—square inches	12,000
Watts per square inch	1.98
Peripheral speed of armature (feet per minute)	2250
Assumed increase of temperature per watt per square inch ...	15 deg.
Estimated rise in temperature	30 "

Spool :

Watts per shunt spool at 60 deg. Cent.	278
„ series „ „	156
Total watts lost per spool, 60 deg. Cent.	434
Cylindrical radiating surface	1350
Watts per square inch of radiating surface	32
Rise of temperature by resistance method per watt per square inch	120 deg. Cent.
Mean temperature rise of spool by resistance method	38.5 „

Commutator :

Area of positive brushes—square inches	25
Amperes per square inch	40
Specific resistance per square inch of contact surface—ohms	0.03
Brush resistance, positive + negative	0.0024
Volts drop at brushes	2.4
C^2R loss at brush contacts	2400
Brush pressure (assumed 1.25 lb. per square inch)	62.5
Coefficient of friction	0.3
Peripheral speed in feet per minute	2040
Brush friction $\dfrac{0.3 \times 2040 \times 62.5}{44.2}$	870
Stray watts lost in commutator	400
Total „ „	3670
Radiating surface in square inches	2400
Watts per square inch radiating surface	1.53
Increase of temperature per watt per square inch of surface assumed	15 deg. Cent.
Estimated increase of temperature	23 „

EFFICIENCY CALCULATIONS

	Watts.
Output, full load	550,000
Armature copper loss	12,700
Core loss	11,000
Commutator loss at brush contacts	2400
Allowance for stray losses in commutator	400
Brush friction loss at commutator	870
Loss in shunt winding	2780
„ series „	1560
„ shunt rheostat	730
„ series diverter	1040
Constant losses	15,780
Variable „	17,700
Total losses	33,480
Efficiency at full load	94.26
„ half load	93.17
„ quarter load	89.05

16-Pole, 1000-Kilowatt Railway Generator

The drawings given in Figs. 190 to 210, on pages 217 to 226, relate to a 1000-kilowatt slow-speed railway generator designed by Mr. H. M. Hobart, and built by the Union Elektricitäts Gesellschaft of Berlin, to whose courtesy the authors are indebted for permission to publish this description.

Several have been installed in England and on the Continent. A photograph of one of the machines supplied to an English specification is reproduced in Fig. 189, on Plate IV.

Specification for 1000-Kilowatt Railway Generator

Number of poles	16
Kilowatts	1000
Revolutions per minute	90
Frequency in cycles per second	12
Terminal volts, full load	500
„ no load	500
Amperes at full load	2000

Dimensions in Inches

Armature:

External diameter	138
Internal „	108
Length over conductors	31.6
Diameter at bottom of slots	135.48
Gross length of armature core	13.8
Effective length „	8.9
Per cent. insulation between laminations	10
Number of ventilating ducts	8
Width of each ventilating duct	10.5
Thickness of laminations	0.025
Pole pitch at surface	27.2
Number of slots	384
Slot pitch at surface	1.13
Width of slot at surface	0.53
„ „ root	0.53
Depth of slot	1.26
Width of tooth at surface	0.6
„ „ root (minimum)	0.57
Bar winding, width of insulated conductor	0.112
„ height „ „	0.494

Cross-section of slot, square inches	0.67
„ „ copper per slot, square inches	0.33
Space factor of slot	0.49
Magnet Core:	
Length of pole face parallel to shaft	13.8
„ „ arc	19.3
Ratio of pole arc to pitch	0.71
Radial length of magnet core	19
Diameter of magnet core	15
Bore of field (diameter)	13,879
Depth of air gap	0.393
Spool:	
Length of spool over flanges	17.5
„ winding space	17.15
Depth of „	2
Available length for shunt spool	13.5
„ „ series spool	3.65
Yoke:	
External diameter over ribs	210
Internal diameter	182
Height of ribs	7.5
Thickness of yoke, exclusive of ribs	6.5
Length of yoke parallel to shaft	19.5
Commutator:	
Diameter	106.5
Number of segments	1152
„ „ per slot	3
Width of segment plus insulation at surface	0.29
Thickness of mica insulation	0.03
Width of segment at surface	0.26
Available length of commutator face	14.5
Brushes:	
Number of sets	16
„ per set	1
Width of the brushes	1.025
Length of arc of contact of brushes...	0.79
Area of contact of one brush, square inches	0.81
„ „ all positive brushes, square inches	51
Material of brush	Carbon

MATERIALS

Armature core	Sheet iron
Spider	Cast iron
Conductors	Copper
Commutator segments	„
„ leads	„

FIG. 189. 16-POLE, 1000-KILOWATT, 500-VOLT RAILWAY GENERATOR. SPEED, 90 REVOLUTIONS.
SHEFFIELD

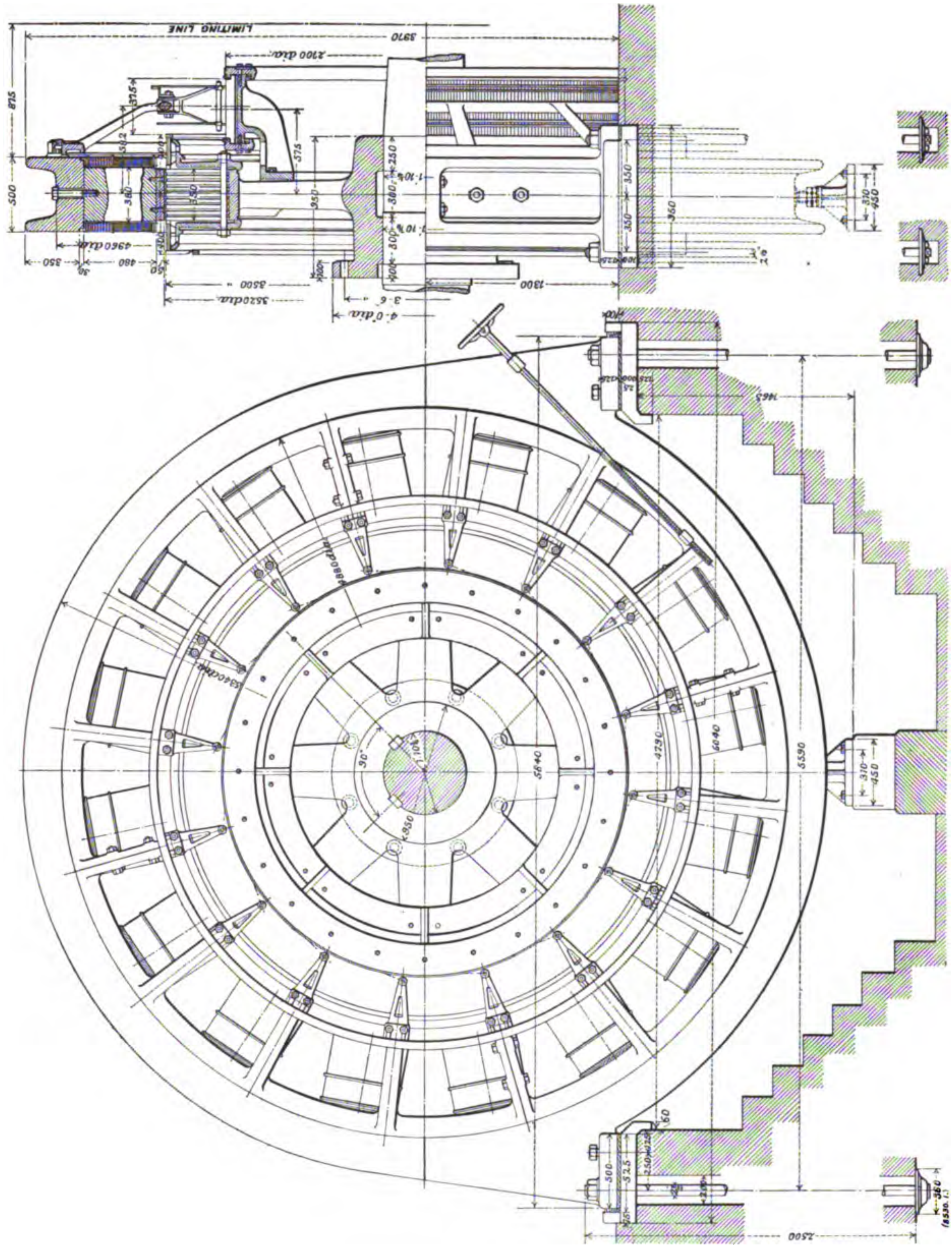


Fig. 190. 16-Pole, 1000-Kilowatt, 500-Volt Railway Generator; Speed, 90 Revolutions (Armature Bolted to Fly-wheel)

Commutator spider	Cast iron
Pole shoes	,,
Yoke	Cast steel
Magnet cores	,,

Technical Data

Armature:

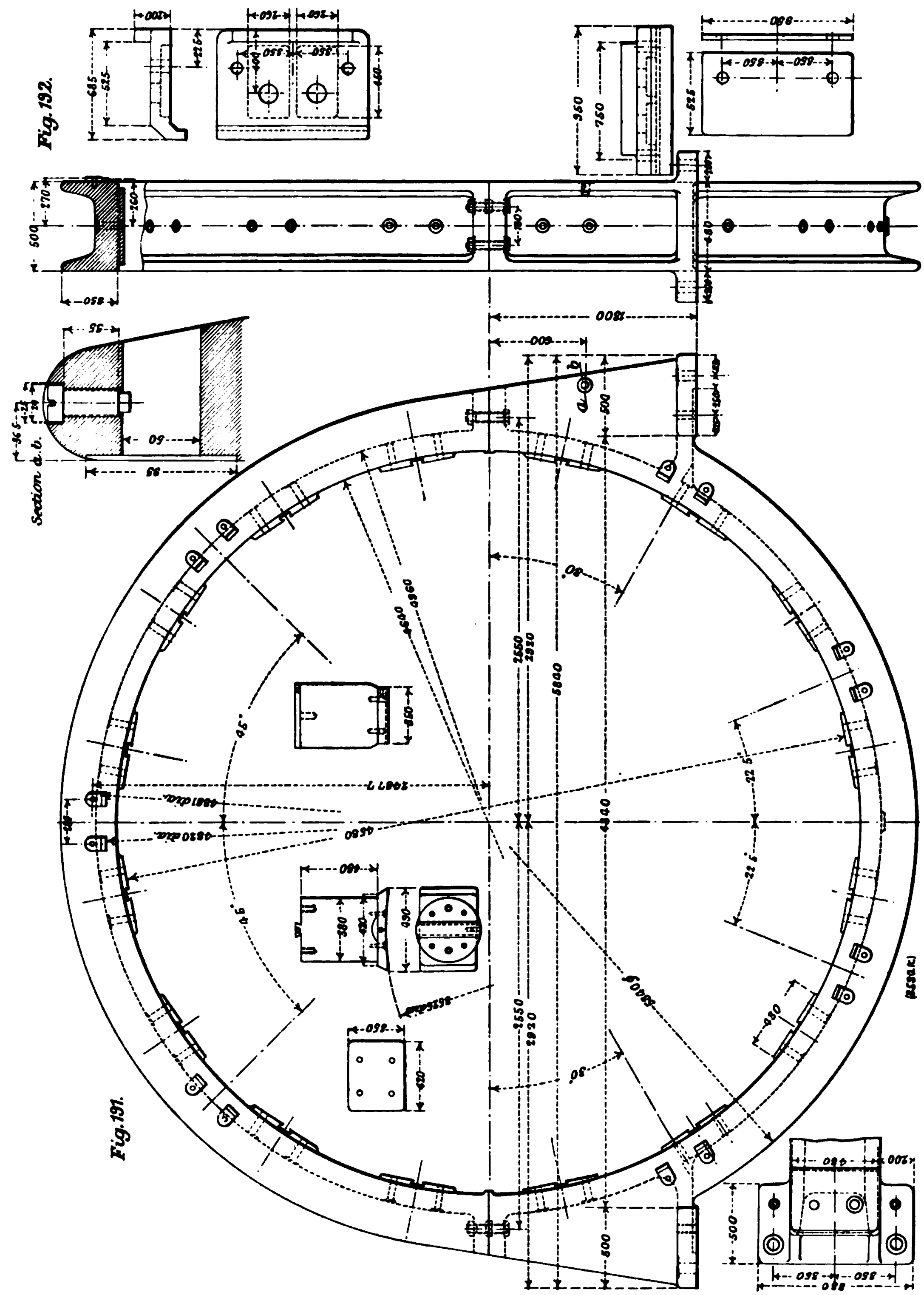
No-load voltage	500
Style of winding	16 circuit single
Gramme ring or drum	drum
Number of paths through winding	16
,, conductors per slot	6
Arrangement ,, ,, ...	3 wide, 2 deep
Amperes per square inch in armature conductors	2220
Total number of face conductors	2304
Total number of turns	1152
Number of turns between brushes	72
Mean length of a single turn	94.5
Cross-section of one conductor, square inches	0.055
Specific resistance at 60 deg. Cent.	0.0000008
Resistance of armature at 60 deg. Cent.	0.00605
Volts drop in ,, ,, ,, ...	12.1
,, brushes and contacts	2.2
,, series winding	1 7
Internal voltage drop, full load	16

Commutator (Sparking Constants):

Periphery of commutator	334
Revolutions per second	1.5
Peripheral speed of commutator (inches per second)	502
Current completely reversed in seconds	0.00158
Frequency of commutation	318
Maximum number of coils short-circuited under one brush ...	3
Length of contact arc of brushes	0.79
Gross length of lamination, λg	13.8
Total lines linked with short-circuited coils = 6 × 20 × 13.8 = C.G.S. lines...	1660
Inductance per segment in henrys	0.0000166
Reactance, ohms	0.0033
Current per armature conductor	125
Reactance voltage, volts	4.13

Magnetic Calculations

Megalines entering armature per pole, no load	14.45
,, ,, ,, full load	14.9
Coefficient of leakage	1.125
Megalines per pole, no load	16.25
,, ,, full load	16.77



FIGS. 191 AND 192. YOKE AND MAGNET CORE OF 16-POLE, 1000-KILOWATT RAILWAY GENERATOR

Armature :

Cross-section in square inches	244
Density at no load	59,500
,, full load	61,500
Magnetic length ...	11.9
Ampere-turns per inch length at no load	8.4
,, ,, ,, full load	9.2
,, in armature at no load	100
,, ,, full load	110

Teeth :

Ratio of pole arc to pole pitch	0.71
Total number of teeth	384
Number of teeth per pole (taking 5 per cent. for spread), $\frac{384}{16} \times .71 \times 1.05 =$	18
Cross-section teeth at root...	93

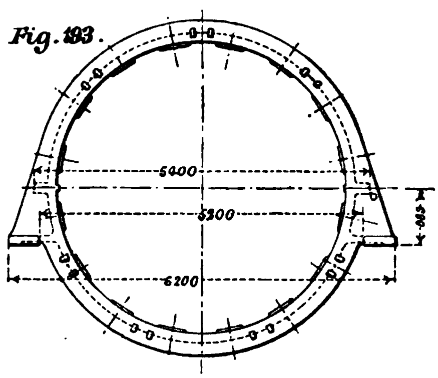
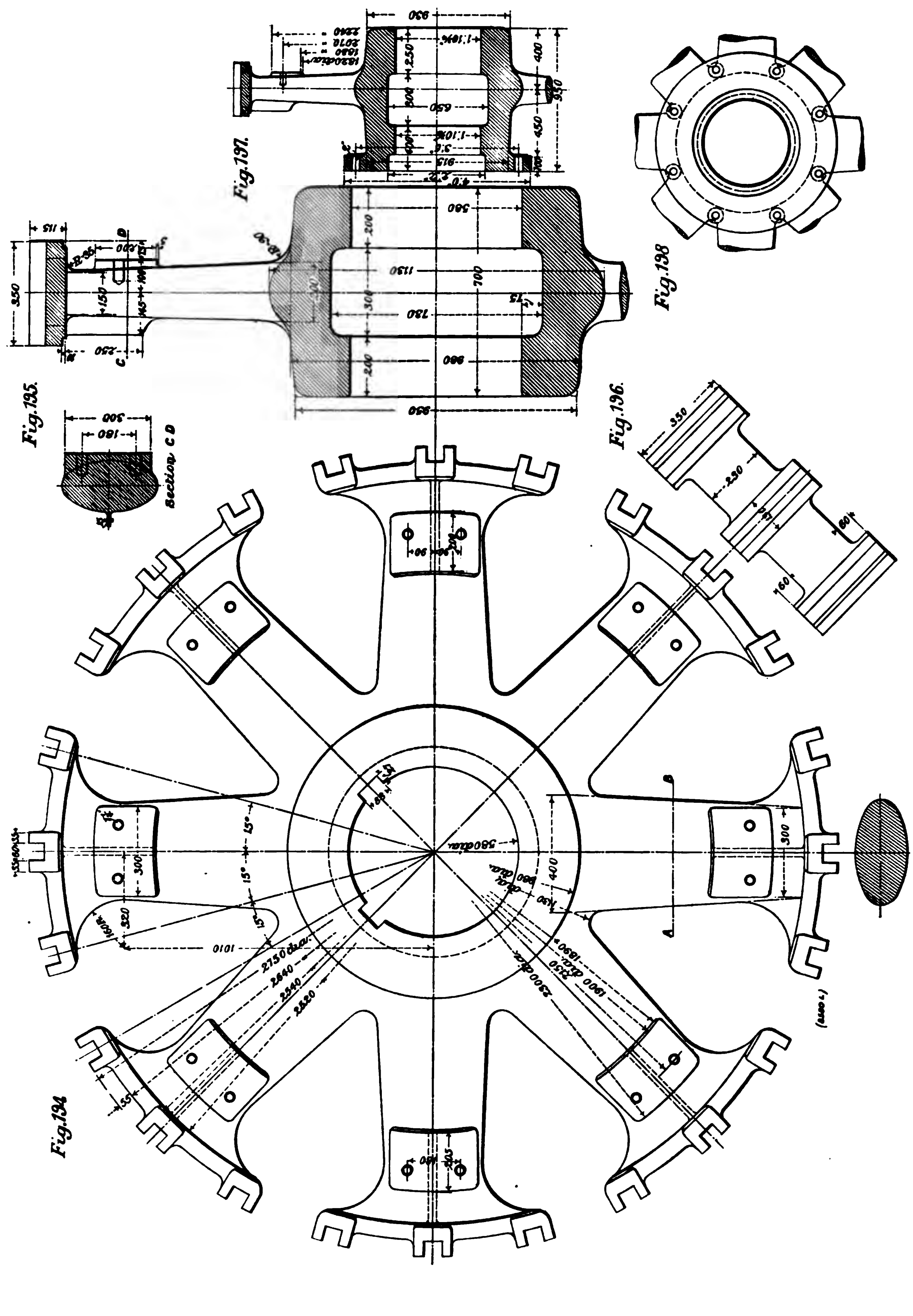


FIG. 193. YOKE OF SIMILAR GENERATOR, OF DIFFERENT DIMENSIONS, FOR A SPECIAL PURPOSE

Apparent density at no load	156,000
,, ,, full load	161,000
Mean width of tooth ÷ width of slot	1.1
Corrected density at no load	142,000
,, ,, full load	147,000
Magnetic length...	1.26
Ampere-turns per inch at no load	1570
,, ,, full load	1900
,, for teeth at no load	2200
,, ,, full load	2400

Magnet Core :

Cross-section, square inches	177
Density at no load	92,000
,, full load	95,000



FIGS. 194 TO 196. ARMATURE SPIDER OF 16-POLE, 1000-KILOWATT RAILWAY GENERATOR
FIGS. 197 AND 198. SHOWING CONSTRUCTION OF ARMATURE BOLTED TO FLY-WHEEL

Magnetic length...	19
Ampere turns per inch, no load	5
„ „ full load	61
„ magnet core, no load	1000
„ „ full load	1150

Yoke:

Cross-section in square inches (excl. ribs)	254
Density, no load	64,000
„ full load	66,000
Magnetic length in inches...	19
Ampere turns per inch, no load	18.8
„ „ full load	20.5
„ for yoke, no load	356
„ „ full load	385

Air Gap:

Cross-section at pole face ...	266
Density at pole face, no load	54,500
„ „ full load	56,200
Magnetic length...	.393
Ampere turns for air gap, no load	6700
„ „ full load...	6900

Ampere Turns per Spool for Saturation:

	No Load.	Full Load.
Armature core	100	110
„ teeth	2,200	2,400
Gap	6,700	6,900
Magnet core	1,000	1,150
„ yoke	400	440
Total	10,400	11,000

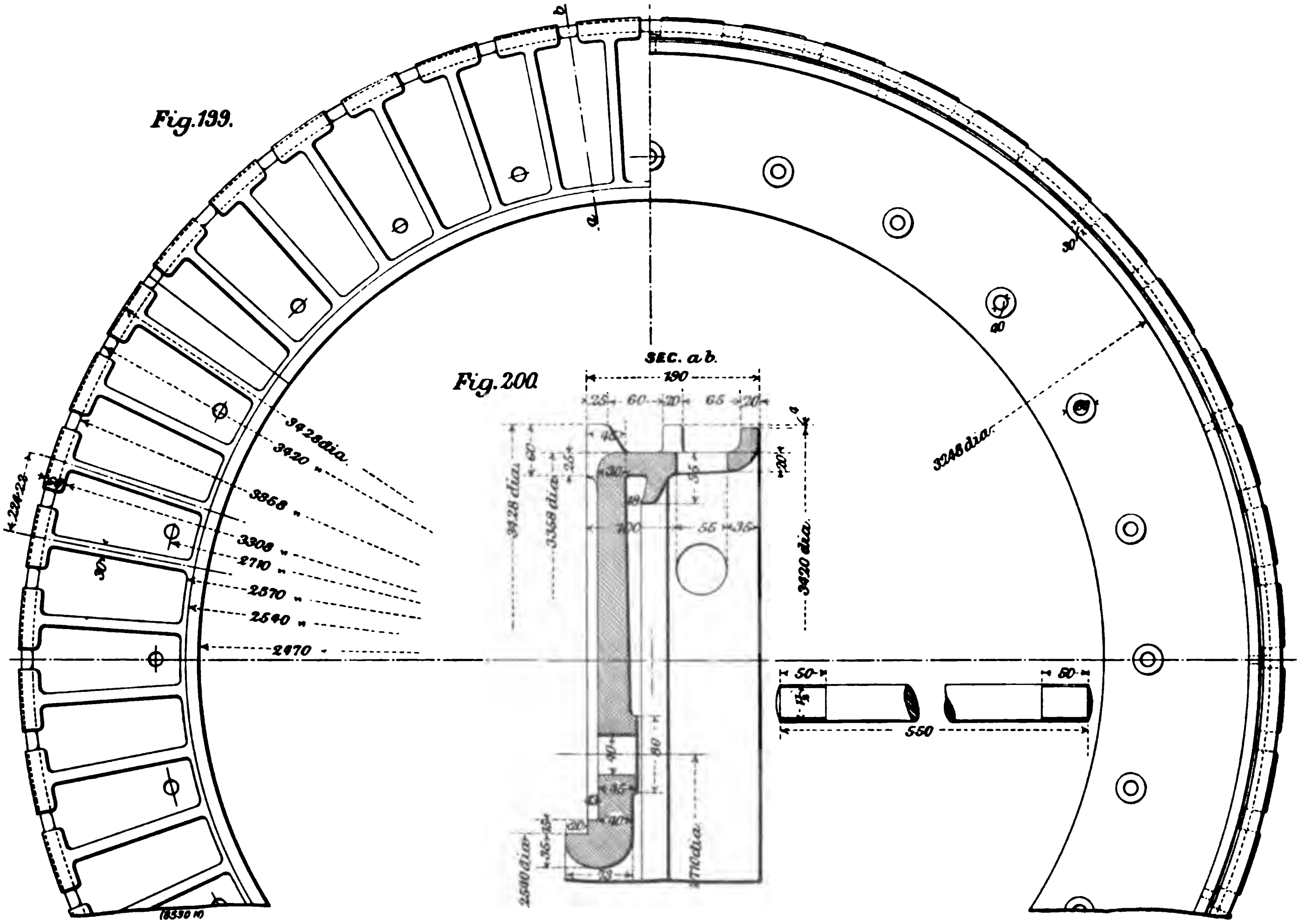
Ampere turns for overcoming ohmic drop = 11,000 - 1,400	600
The shunt-winding ampere turns are taken as	11,000

Armature Interference:

Ampere turns per pole	72
Amperes per circuit	125
Ampere turns per pole	9000
Segments lead of brushes...	7.2
Percentage lead of brushes	10
Apparent tooth density, full load	161,000
Saturation of Field ampere turns, no load (K)	11,000
Ampere turns to overcome ohmic drop (H)	600
Demagnetising ampere turns per pole (G)	1800
Total distorting ampere turns per pole (D)	7100
Ampere turns for teeth and gap (S)	9300
$D \div S =$	0.76
$F \div D =$	0.21
Field ampere turns to overcome distortion (F)	1500
Total ampere turns, full load (F + C + H + K)	14,900

Shunt Spool:

Mean length of one turn in inches	54
" " " feet	4.5
External diameter of spool	19.2
Internal " "	15.25
Mean diameter of spool	17.225
Ampere turns per shunt spool	11,000
Ampere feet	49,500



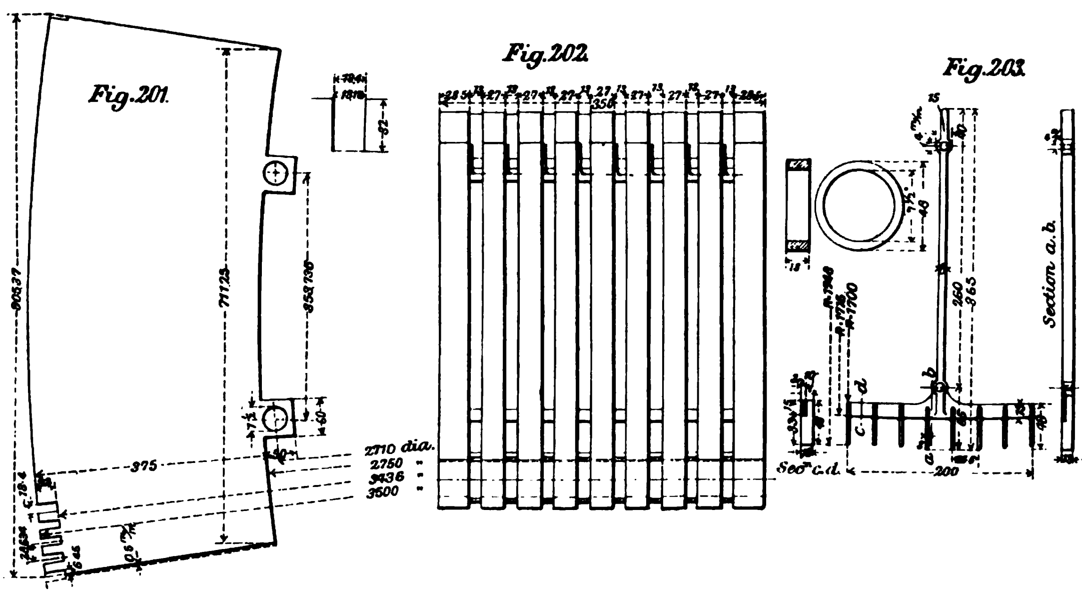
FIGS. 199 AND 200. END-FLANGE OF 16-POLE, 1000-KILOWATT RAILWAY GENERATOR

Watts at 60 deg. Cent. $35.6 \times \dfrac{\left(\dfrac{49{,}500}{1{,}000}\right)^2}{168}$	515
Watts lost in shunt and rheostat	9500
Amperes per shunt spool	19
Turns " "	580
Resistance per shunt spool at 60 deg. Cent.	1.44
" " 16 shunt spools at 60 deg. Cent.	23
Length of wire per spool	2630
B.W.G.	No. 9

Bare diameter	0.148
D.C.C. „	0.16
Cross-section in square inches	0.0172
Amperes per square inch	1100
Winding space for shunt, inches	14
Number of layers	7
„ turns per layer	83
Depth of winding	1.15
Weight of shunt copper per spool in pounds	173
„ „ for all spools in pounds	2750

Shunt Rheostat:

Current in rheostat	19
Resistance of rheostat, ohms	3.42
C^2R loss in rheostat	1250



FIGS. 201 TO 203. LAMINATIONS AND VENTILATING PIECES OF 16-POLE, 1000-KILOWATT RAILWAY GENERATOR'

Series Spool:

Ampere turns per series spool	3900
Amperes per series spool	1650
Number of turns per series spool	$2\frac{1}{2}$
Mean length of one turn	54
Total length of series winding, in feet	11.3
Cross-section of one series turn	0.122
„ fourteen series turns in parallel	1.70
Amperes per square inch	980
Resistance of one series spool at 60 deg. Cent.	0.0000625
„ 16 series spools at 60 deg. Cent.	0.001
Watts lost in series spools at 60 deg. Cent.	2700

Radiating surface of series spools ...	1140
Watts per square inch of surface ...	2.38
Series conductor ...	0393 × 3.15
Total weight of series copper, in pounds ...	1200

Series Diverter:

Resistance at 60 deg. Cent., ohms ...	0.00465
Amperes in diverter ...	350
Watts lost in diverter ...	580
" series spool ...	2700
Total watts lost in compounding ...	3280

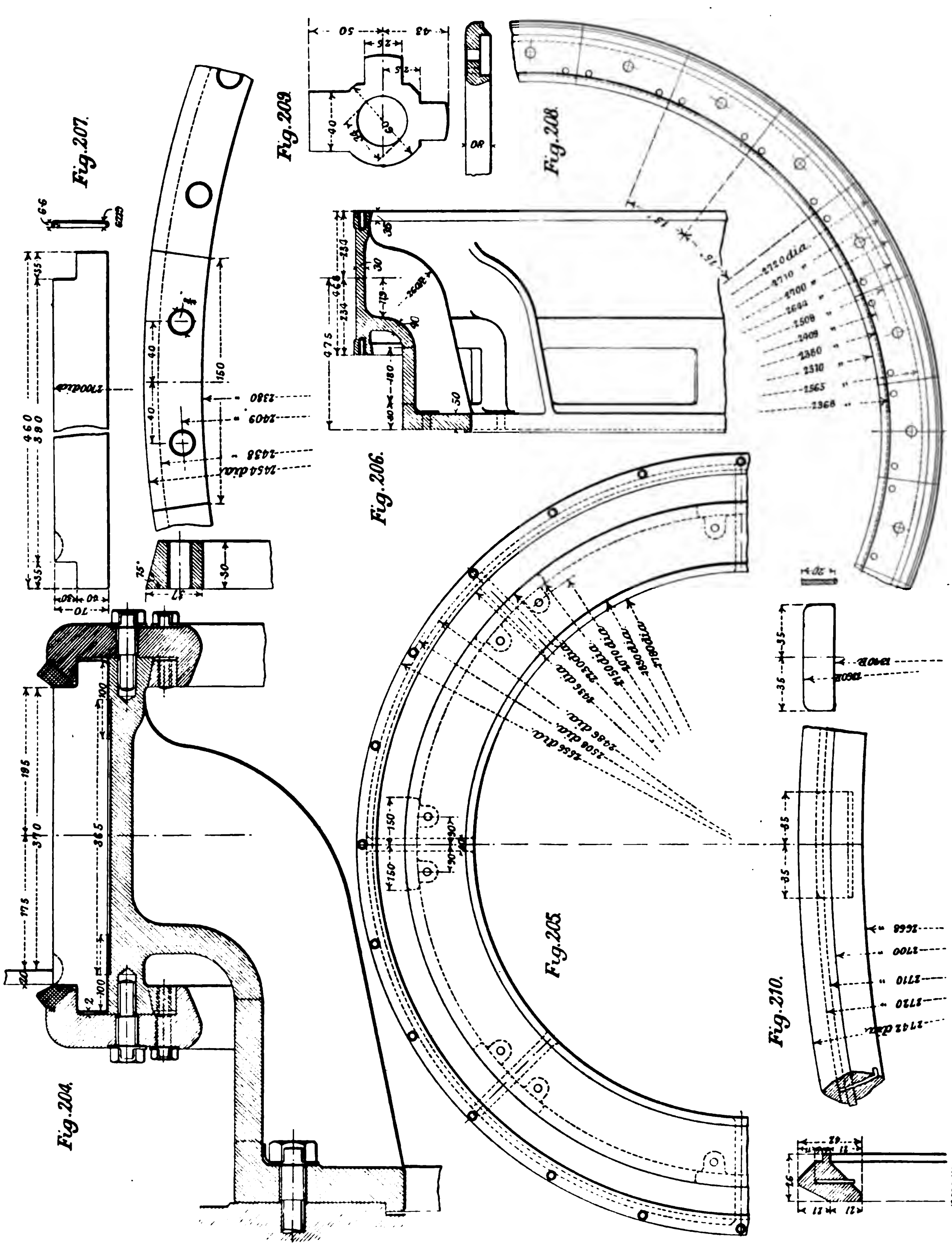
Thermal Calculations

Armature:

Current in armature ...	2000
Resistance of armature at 60 deg. Cent. ...	0.00605
C^2R loss of armature at 60 deg. Cent. ...	24,200
Density in core, full load ...	61,500
Cycles per second ...	12
$\frac{\text{Density} \times \text{cycles per second}}{1000}$ ...	740
Watts per pound, from core loss curve ...	1.36
Weight of core laminations ...	13,200
Watts iron loss ...	18,000
Total loss in armature ...	42,200
Peripheral radiating surface of armature, square inches ...	13,600
Watts per square inch ...	3.1
Peripheral speed of armature, feet per minute ...	3240
Assumed increase of temperature per watt per square inch ...	11.3 deg. Cent.
Estimated rise in temperature ...	35 "

Commutator:

Area of positive brushes, square inches ...	51
Amperes per square inch ...	39.3
Specific resistance per square inch of brush surface, ohms ...	0.03
Brush resistance (positive × negative) ...	0.00110
Volts drop at brush contacts ...	2.2
C^2R loss " ...	4400
Brush pressure (assumed 1.63 lb. per square inch) ...	165
Coefficient of friction ...	0.3
Peripheral speed of commutator in feet per minute ...	2800
Brush friction $= \frac{.3 \times 2500 \times 165}{44.2}$ ...	2800 watts
Allowance for stray losses in commutator ...	200
Total watts lost in commutator ...	7400
Radiating surface ...	4800
Watts per square inch ...	1.54
Increase of temperature per watt per square inch of surface ...	20 deg. Cent.
Estimated increase of temperature ...	31 "



Figs. 204 to 210. Commutator and its Component Parts for 16-Pole, 1000-Kilowatt Railway Generator

EFFICIENCY CALCULATIONS

	Watts.
Output, full load	1,000,000
Core loss	18,000
Armature copper loss	24,200
Commutator loss at brush contacts	4,400
Allowance for stray losses in commutator	200
Brush friction loss at commutator	2,800
Loss in shunt winding	8,250
„ series winding	2,700
„ shunt rheostat	1,250
„ series diverter	580
Total constant losses	30,500
„ variable losses	31,880
„ losses	62,380
Efficiency, full load	94.15
„ half load	92.85
„ quarter load	88.52

Weights in Pounds:

Armature copper	1980
Field copper	3950
Commutator segments	4200
Armature laminations	13,200
Pole face	2200
Magnet cores	15,400
Magnet yoke (including feet)	33,000

SIX-POLE 250-KILOWATT ELECTRIC GENERATOR

The following is one of the latest designs: In Figs. 211 to 224, pages 228 to 232, are given diagrammatical sketches, setting forth the electromagnetic dimensions to which the ultimate designs should correspond. Figs. 225 to 233, pages 235 to 238, show some interesting details of construction of frame, spider, commutator, brush holders, bearing, &c., suggested among other alternative schemes, in the mechanical development of the generator.

SPECIFICATION

Number of poles...	6
Kilowatts	250
Revolutions per minute	320
Frequency in cycles per second	16
Terminal volts, full load	550
„ „ no load	500
Amperes	455

Fig. 212

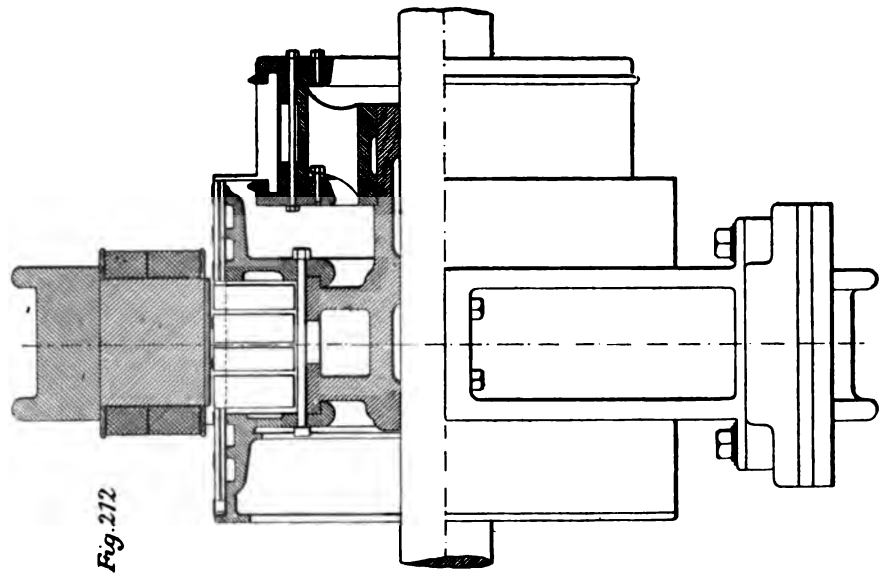
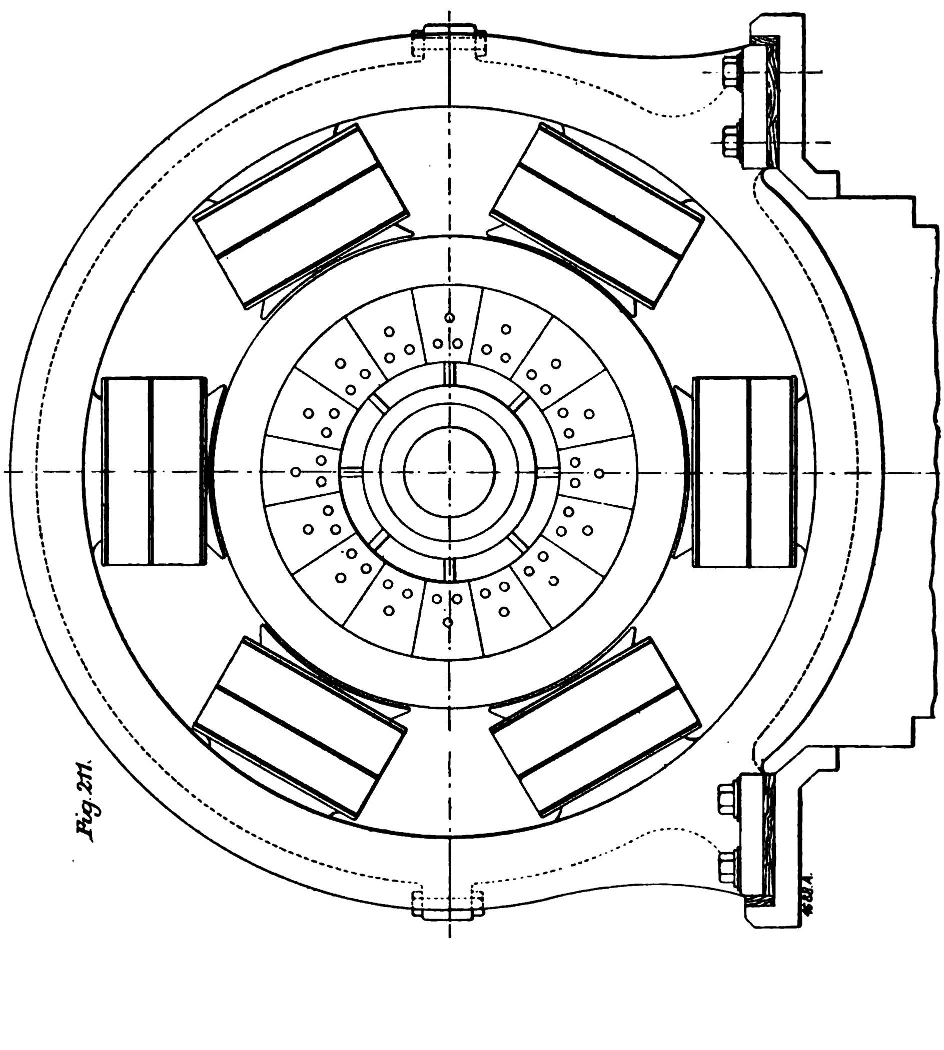


Fig. 211

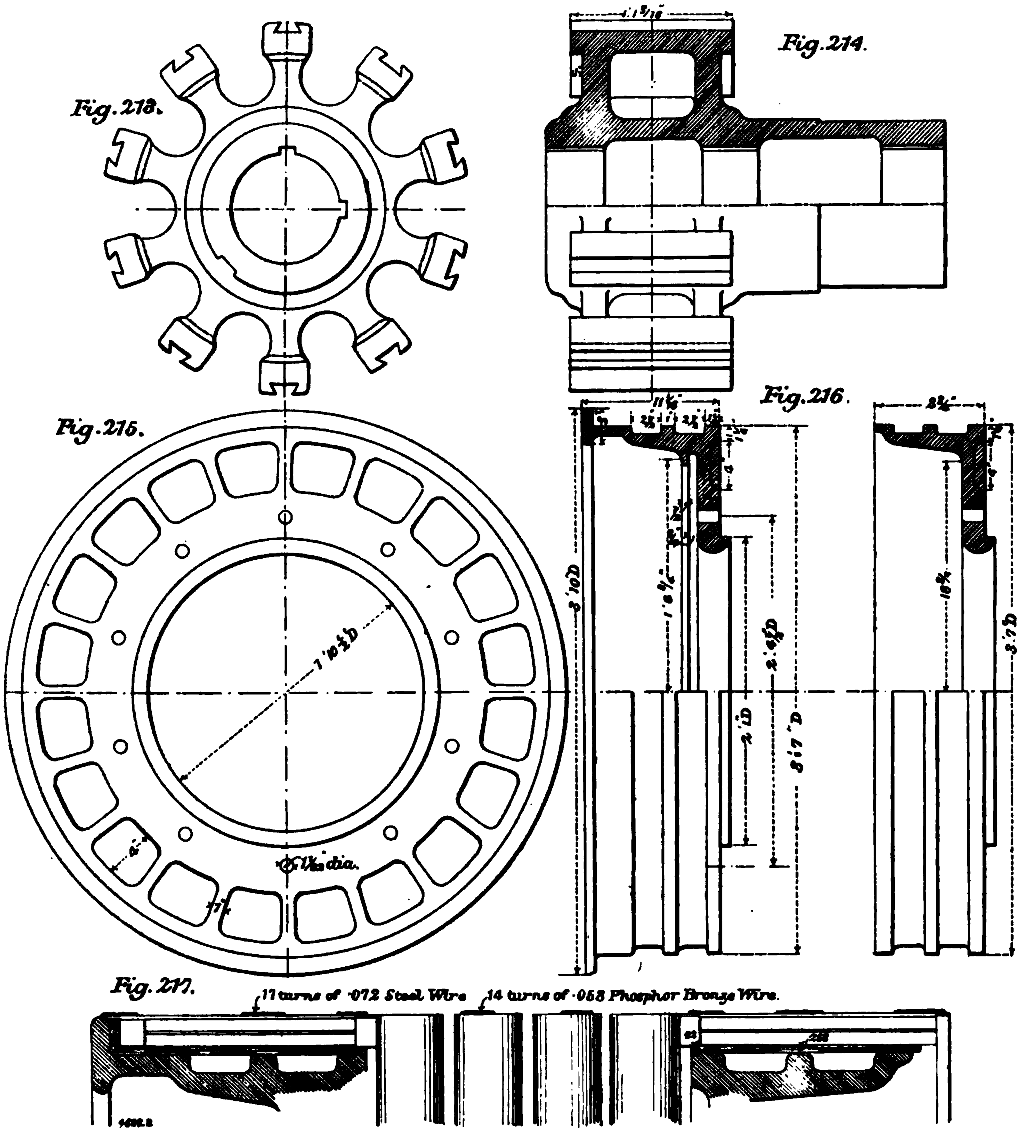


Figs. 211 and 212. Six-Pole, 250-Kilowatt, 320 Revolutions per Minute Continuous-Current Generator

Dimensions

Armature:

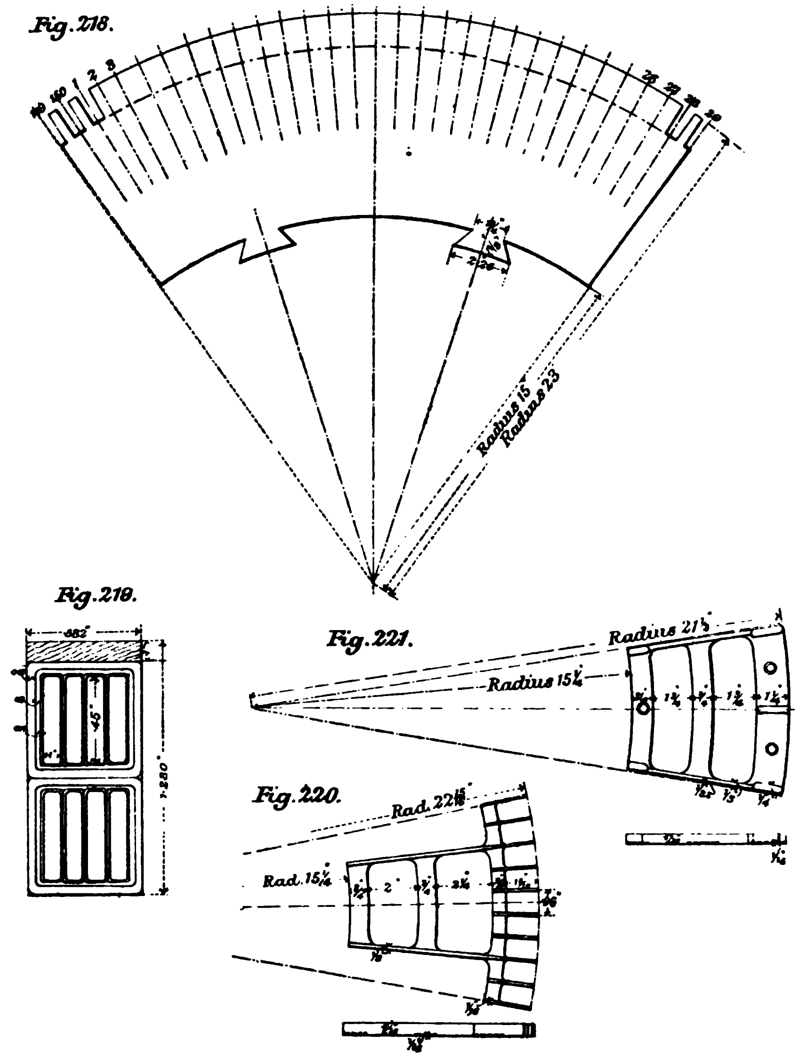
Diameter over all	46 in.
Length over conductors	32.3 „
Diameter at bottom of slots	43.4 „
Internal diameter of core	30 „



Figs. 213 to 217. Details of Armature of 6-Pole, 250-Kilowatt, 320 Revolutions per Minute Continuous-Current Generator

Length of core over all	12.3 in.
Effective length, magnetic iron	9.9 „
Pitch at surface	24 „
Insulation between sheets...	10 per cent.

Thickness of sheets	0.014 in.
Depth of slot	1.28 „
Width of slot at root	0.582 „
„ „ surface	0.582 „
Number of slots	150
Minimum width of tooth	0.327 „



FIGS. 218 TO 221. DETAILS OF ARMATURE OF 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

Width of tooth at armature face	0.379 in.
Width of conductor	0.10 „
Depth of conductor	0.45 „
Number of ventilating ducts	3
Width of each ventilating duct	0.44 „
Efficient length of core ÷ total length	0.80 „

Magnet core, length of pole face	12.3
Length of pole arc	17 in.
Pole arc ÷ pitch	0.70
Thickness of pole-piece at edge of core	0.50
Radial length, magnet core	10.5
Diameter of magnet core	12.3
Bore of field (diameter)	$46\frac{5}{8}$ in.
Depth of air gap	$\frac{5}{16}$ "

Spool:

Length over flanges	10.5 in.
" of winding space	9.3 "
Depth	2.75 "

Yoke:

Outside diameter	81.1 in.
Inside "	72.1 "
Thickness	4.5 "
Length along armature	15 "

Commutator:

Diameter	37.4 "
Number of segments	600
" " per slot	4
Width of segment at commutator face	0.167 in.
Thickness of mica insulation	0·030 "
Available length surface of segment	9.06 "
Cross-section commutator leads	0.03 square inch

Brushes:

Number of sets	6
" in one set	4
Width of brush	1.75 in.
Thickness of brush	0.625 "
Area of contact one brush	1.09 square inches
Type of brush	Carbon

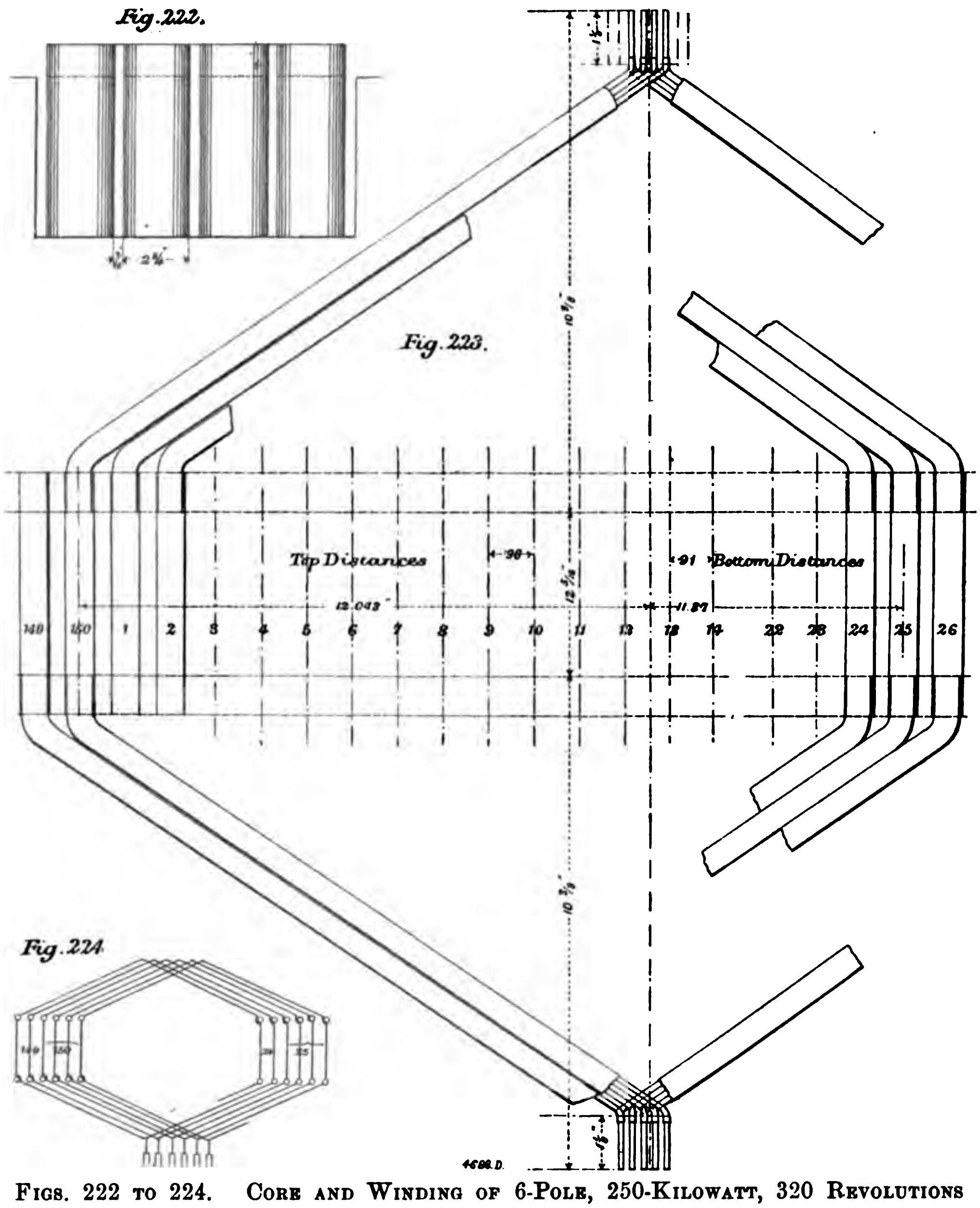
MATERIALS

Armature core	Sheet iron
Spider	Cast iron
Conductors	Copper
Commutator segments	"
" leads	"
" spider	Cast iron
Pole-pieces	Cast steel
Yoke	"
Magnet cores	"
Brushes	Carbon

TECHNICAL DATA

Armature:

No load voltage ...	500
Number face conductors	1200
Conductors per slot	8



FIGS. 222 TO 224. CORE AND WINDING OF 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

Number of circuits	6
Style winding ...	Multiple
Gramme ring, or drum	Drum

Type of construction of winding	Barrel-wound
Mean length, one armature turn	84.5 in.
Total armature turns	600
Turns in series between brushes	100
Length between brushes	8450 in.
Cross-section one armature conductor	0.045 sq. in.
Ohms per cubic inch at 20 deg. Cent.	0.00000068
Resistances between brushes at 20 deg. Cent.	0.0213 ohms
„ „ 60 „	0.0245 „
Volts drop in armature at 60 deg. Cent.	11.3
„ brushes and contacts	2.1
Total internal voltage, full load	564
Amperes per square inch in armature winding	1700
„ „ commutator connections	2500

Commutation :

Average voltage between commutator segments	5.5
Armature turns per pole	100
Amperes per turn	76
Armature ampere turns per pole	7600
Segments lead of brushes	8
Percentage „	8 per cent.
„ demagnetising ampere turn	16 „
„ distorting „ „	84 „
Demagnetising ampere turns per pole	1220
Distorting „ „	6380
Frequency of commutation, cycles per second	500
Number of coils simultaneously short-circuited per brush ...	4
Turns per coil	1
Number of conductors per group simultaneously undergoing commutation	8
Flux per ampere turn per inch length armature lamination ...	20
Flux linked with eight turns with one ampere in these turns ...	1970 lines
Inductance of one turn in henrys = $1 \times 1970 \times 10^{-8}$	0.0000197
Reactance short-circuited coil	0.062 ohms
„ voltage short-circuited coil	4.7 volts

Magneto-Motive Force Calculations

Megalines entering armature, per pole piece, no load	7.80
„ „ „ „ full load	8.80
Coefficient of magnetic leakage	1.15
Megalines in magnet frame, per pole piece, no load	8.97
„ „ „ „ full load	10.1

Armature :

Section	132 sq. in.
Length, magnetic	13.0 „

Density, no load	59 kilolines
„ full load	66 „
Ampere turns per inch length, no load	11
„ „ „ full load	13
„ no load	140
„ full load	179

Teeth:

Transmitting flux from one pole	20
Section at roots	65
Length	1.28
Apparent density, no load	132 kilolines
„ „ full load	148 „
Corrected „ no load	124 „
„ „ full load	134 „
Ampere turns per inch length, no load	700
„ „ „ full load	1250
„ no load	890
„ full load	1600

Gap:

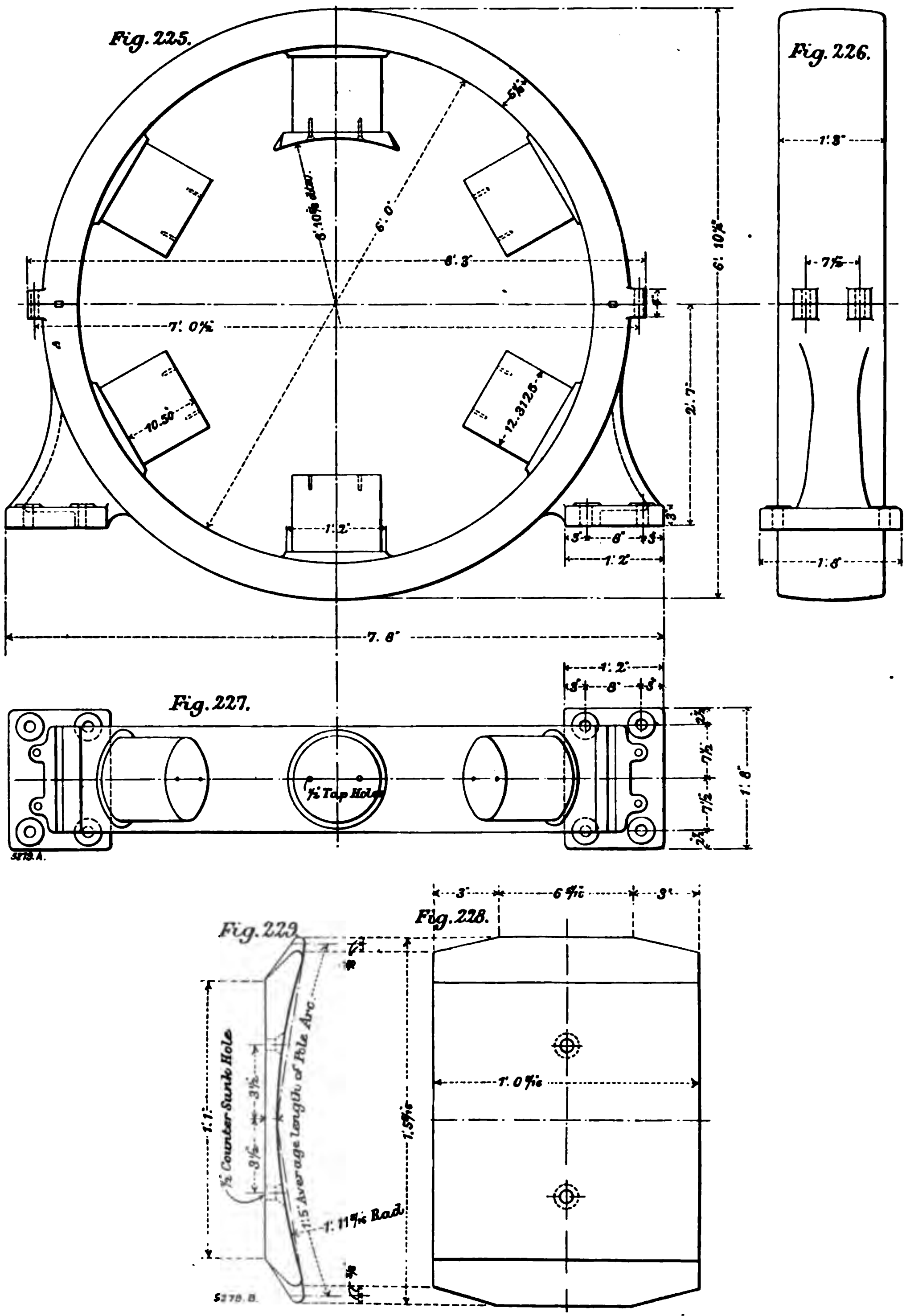
Section at pole-face	210 sq. in.
Length gap	0.31 in.
Density at pole-face, no load	37.2 kilolines
„ „ full load	42 „
Ampere turns, no load	3640
„ full load	5150

Magnet Core:

Section	119 sq. in.
Length (magnetic)	12.75 in.
Density, no load	76 kilolines
„ full load	85 „
Ampere turns per inch length, no load	35
„ „ „ full load	46
„ no load	450
„ full load	590

Magnetic Yoke:

Section	140 sq. in.
Length per pole	18 in.
Density, no load	64 kilolines
„ full load	72 „
Ampere turns per inch length, no load	25
„ „ full load	32
„ no load	450
„ full load	570



FIGS. 225 TO 229. MAGNET FRAME AND POLE SHOES FOR 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

SATURATION AMPERE TURNS PER SPOOL

	No Load and 500 Volts.	No Load and 564 Volts, Corresponding to Internal Voltage at Full Load, when Terminal Voltage is 550.
Armature core	140	170
„ teeth	890	1600
Gap	3640	4150
Magnet core	450	590
„ yoke	450	570
	5570	7080

Demagnetising ampere turns per pole, at full load ...	1220
Allowance for increase in density through distortion ...	700
Total ampere turns at full load and 550 terminal volts ...	8920

If the rheostat in the shunt circuit is adjusted to give 5570 ampere turns at 500 volts, then when the terminal voltage is 550 the shunt excitation will amount to $\frac{550}{500} \times 5570 = 6130$ ampere turns.

$8900 - 6130 = 2770$ ampere turns, must be supplied by the series-winding.

CALCULATION OF SPOOL WINDING

Shunt :

Mean length of one shunt turn	= 48.5 in. = 4.05 ft.
Ampere turns per shunt spool at full load	6,130
Ampere feet	24,800
Total radiating surface of one field spool	530 square inches
Proportion available for shunt $= \frac{6130}{8900} \times 530$ ...	= 365 „
Permit .40 watts per square inch at	20 deg. Cent.
$\therefore 365 \times .40 = 146$ watts per shunt spool at	20 „
And 168 watts per shunt spool at	60 „

$$\text{Shunt copper per spool} = \frac{31 \times 615}{146} = 131 \text{ lb.} \left[\text{Lb.} = \frac{31 \times \left(\frac{\text{amp. feet}}{1000}\right)^2}{\text{watts.}}\right]$$

Plan to have 80 per cent. of the available 550 volts, *i.e.*, 440 volts at the terminals of the field spools when hot, the remainder being consumed in the field rheostat. This is 382 volts at 20 deg. Cent., or 63.5 volts per spool. Hence require $\frac{146}{63.5} = 2.3$ amperes per spool.

Turns per shunt spool $= \frac{6130}{2.3}$ ... ... =	2660
Length of 2660 turns	10,800 ft.
Pounds per 1000 ft.	12.1
No. 14 B. and S. has 12.4 per 1000 ft.	
Bare diameter	0.0641 in.
D.C.C. „	0.075 „
Cross-section	0.00323 square inch
Amperes per square inch	710

Length of the portion of winding space available for shunt winding, 6.5 in.
Winding consists of 33 layers of 81 turns each, of No. 14 B. and S.

Series Winding

The series winding is required to supply 2770 ampere turns at full load of 455 amperes.

Planning to divert 25 per cent. through a rheostat in parallel with the series winding, we find we have $.75 \times 455 = 342$ amperes available for the series excitation; hence each series coil should consist of $\frac{2770}{342} = 8$ turns.

Mean length of series turn	48.5 in.
Total length of eight turns	388 „
Radiating surface available for series spool	165 square inches

Permit .40 watt per square inch in series winding at 20 deg. Cent.
Watts lost per series spool at 20 deg. Cent. $= .40 \times 165 = 66$.
Hence resistance per spool at 20 deg. Cent. $= \frac{66}{342^2} = .00057$ ohms.
Copper cross-section = .46 square inch.
Series winding per spool may consist of eight turns made up of four strips of sheet copper 2.3 in. × .050 in.
Weight of series copper in one spool = 58 lb.
Current density series winding = 740.

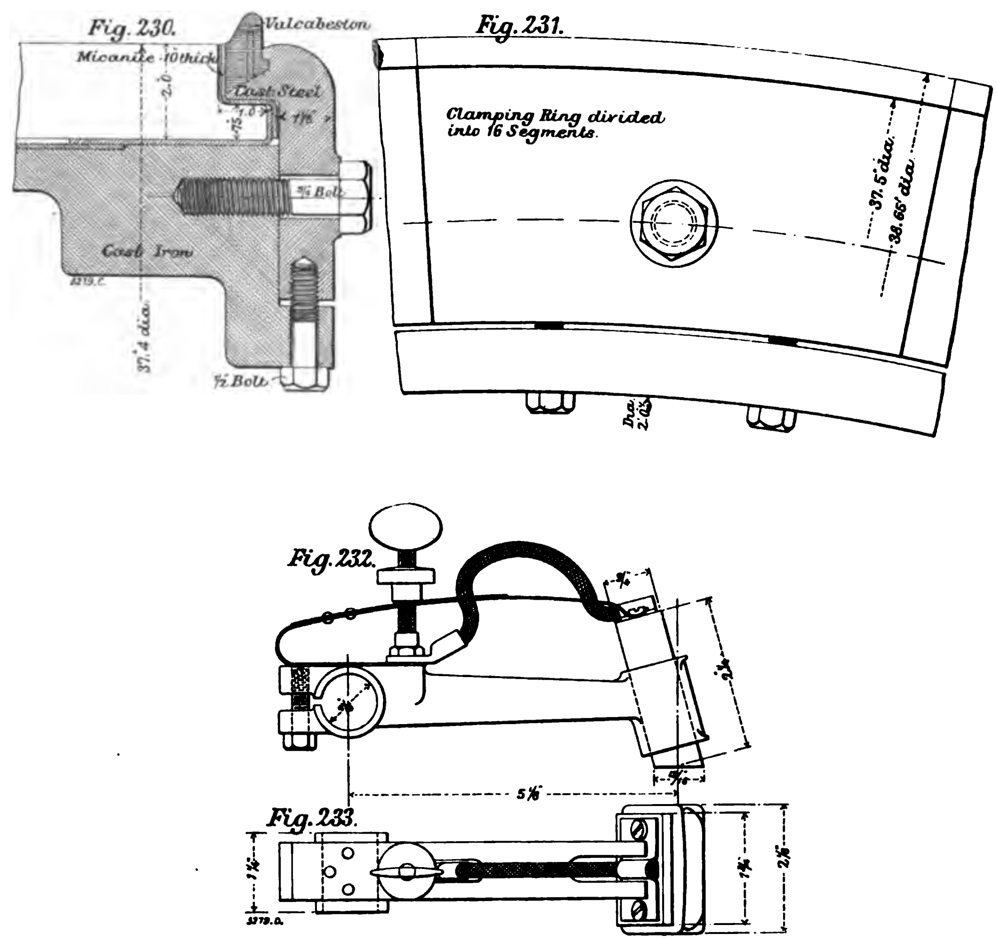
Thermal Calculations

Armature:

C^2 R loss at 60 deg. Cent.	5050 watts
Core loss	4000 „
Total armature loss	9050 „
Peripheral radiating surface of armature	4700 square inches
Watts per square inch radiating surface	1.93
Peripheral speed armature feet per minute	3850
Assumed increase of temperature per watt per square inch in radiating surface as measured by increased resistance =	25 deg. Cent.
Hence estimated total increase temperature of armature =	48 „

Commutator:

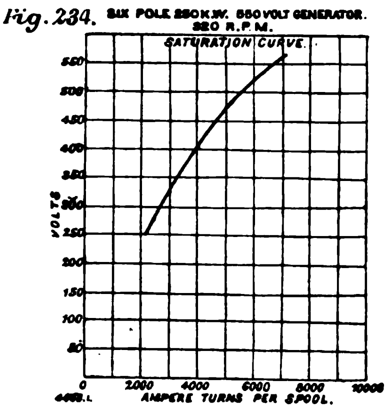
Area of all positive brushes	13.1 square inches
Amperes per square inch brush-bearing surface	35 amperes
Ohms per square inch bearing surface carbon brushes	0.3 ohm
Brush resistance, positive and negative	0.0046 „
Volts drop at brush contacts	2.1 volts
C^2 R at brush contacts	950 watts
Brush pressure, assumed 1.25 lb. per square inch	32.8 lb.

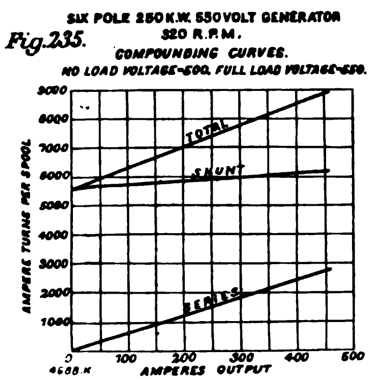


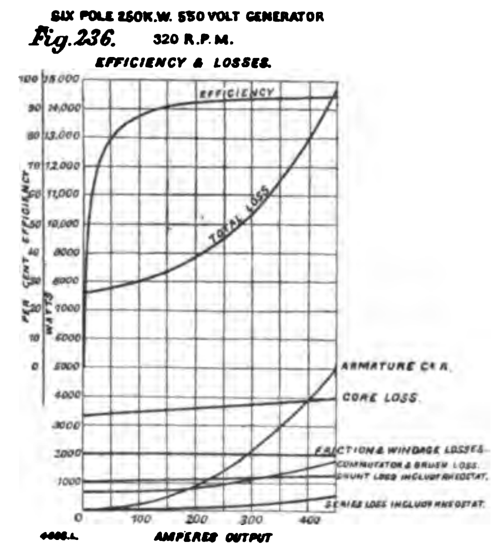
FIGS. 230 TO 233. COMMUTATOR AND BRUSH HOLDER FOR 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

Coefficient friction	0.3
Peripheral speed of commutator, feet per minute	3130
Brush friction	700 watts
Allowance for stray power lost in commutator	150 „
Total commutator loss	1800 „
Radiating surface in square inches	1100

Watts per square inch radiating surface of commutator ...	1.64
Increase of temperature per watt per square inch radiating surface	20 deg. Cent.
Total estimated increase of temperature of commutator ...	33 „ „







FIGS. 234 TO 236. ESTIMATED CURVES FOR 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

EFFICIENCY CALCULATION

	Watts.
Output, full load	250,000
Core loss	4,000
Commutator and brush losses	1,800
Armature C^2R at 60 deg. Cent.	5,050
Shunt spools C^2R at 60 deg. Cent.	1,000
„ rheostat at 60 deg. Cent.	250
Series spools C^2R at 60 deg. Cent.	460
„ rheostat at 60 deg. Cent.	150
Friction in bearings, and windage	2,000
	264,710
Commercial efficiency at full load and 60 deg. Cent.	94 per cent.

WEIGHTS

	Lb.
Armature:	
Magnetic core	2100
Teeth	210
Spider	860
Shafting	1700
End flanges	750
Copper	730
Commutator:	
Segments	680
Spider	530
Rings	260
Other parts of armature and commutator	180
Armature complete, including commutator and shaft	8000

Fig. 237.

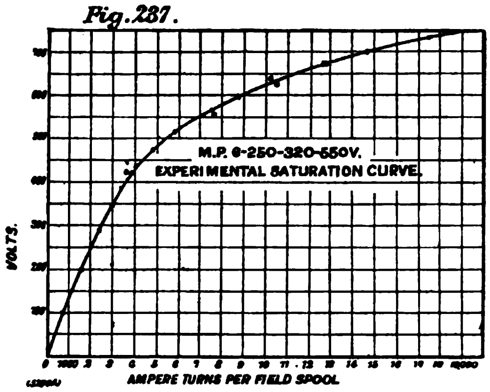
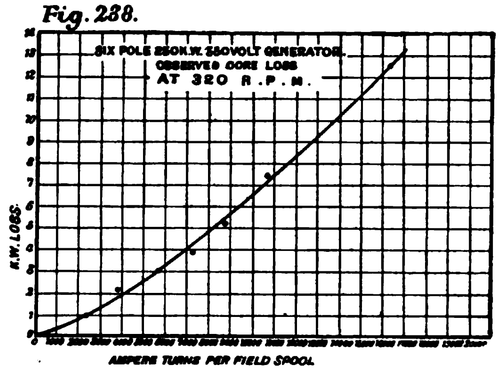


Fig. 238.



FIGS. 237 AND 238. TEST RESULTS FOR 6-POLE, 250-KILOWATT, 320 REVOLUTIONS PER MINUTE CONTINUOUS-CURRENT GENERATOR

Field:	
Six pole-pieces and magnet core	2400
Magnet yoke	5000
Six shunt coils	790
Six series coils	350
Total spool copper	1140
Brush gear	300
Bedplate and bearings	2600
Machine complete	20,000

In Figs. 234, 235, and 236, on page 239, are given saturation, compounding, and efficiency curves in accordance with estimated values. Figs. 237 and 238 show the results of saturation and core loss tests. They agree very well with the predetermined values of the above specification. As shown in Fig. 237, the excitation required at no load and 500 volts was, by observation, 5400 ampere turns, as against the predetermined value of 5570 ampere turns given in the calculation on page 236.

6-Pole, 50-Kilowatt, 525-Volt, 725 Revolutions per Minute, Continuous-Current Generator

Through the courtesy of the British Thomson-Houston Company, we are permitted to publish the following description of a 6-pole, 50-kilowatt, 525-volt, 725 revolutions per minute, continuous-current generator, designed by Mr. David P. Thomson. The machine constitutes the generator component of a motor-generator set designed for the sub-stations of the Yorkshire Power Company. The motor is an 8-pole induction motor, running from a 50-cycle circuit; hence the speed at no load is 750 revolutions per minute, and this decreases to 725 revolutions per minute at full load. The dynamo is compounded to give with this 3½ per cent. drop in speed, a 5 per cent. increase in voltage from 500 volts at no load to 525 volts at full load.

Outline drawings of the dynamo are given in Fig. 239, and a photograph of the set is reproduced in Fig. 240, Plate V.

The designing specification of the machine is given below:—

Specification

Number of poles	6
Normal rating in kilowatts	50
Speed in revolutions per minute	725
„ „ second	12.1
Periodicity in cycles per second	36.3
Terminal voltage, full load	525
„ „ no load	500
Amperes output, full load	100

Dimensions in Inches

Armature:

External diameter	20¼
Axial length of the winding	15
External diameter of the laminations	20¼
Diameter at the bottom of the slots	18.29
Internal diameter of the laminations	11½
Axial length of core between flanges	7.625
Effective length of core (magnetic iron)	6.52
Circumference (external)...	64.5
Pitch at circumference	10.8
Circumference at the bottom of the slots	57.5
Insulation between laminations, per cent.	10
„ „ „ material	Varnish
Thickness of punchings	0.02
Depth of the slot	0.98

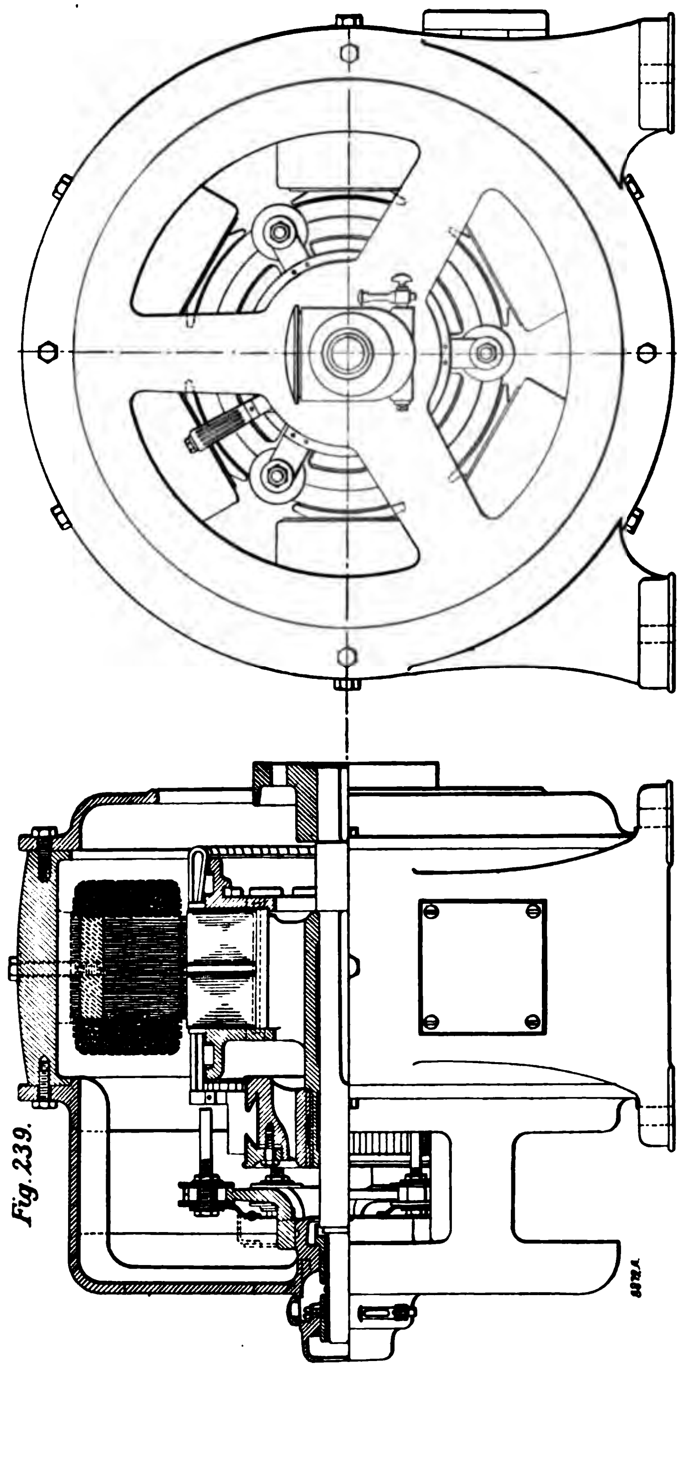
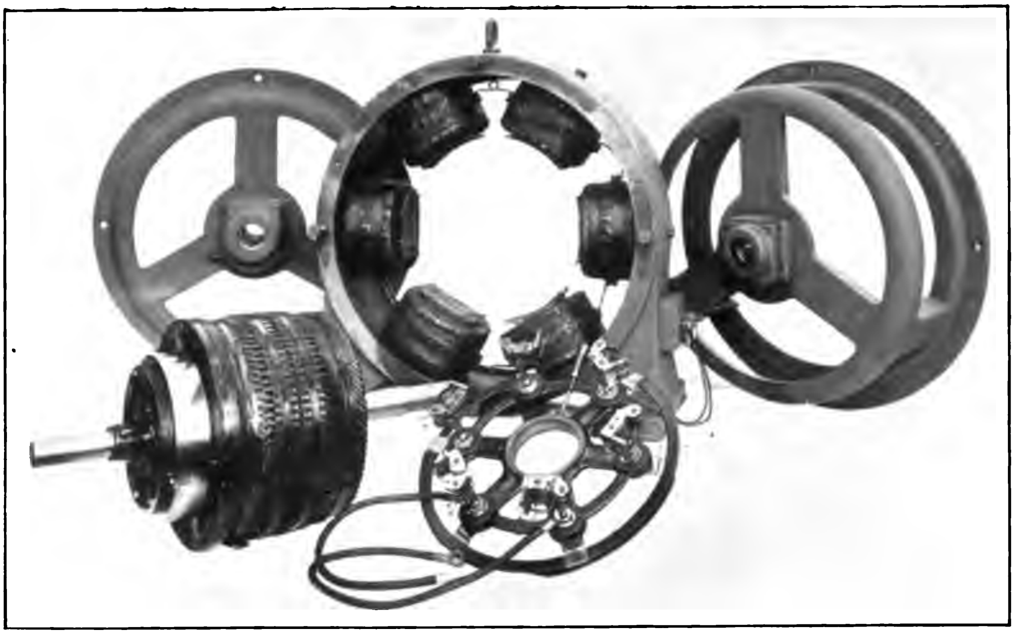


FIG. 239. SIX-POLE, 50-KILOWATT, 525-VOLT, 725 REVOLUTIONS PER MINUTE, CONTINUOUS-CURRENT GENERATOR



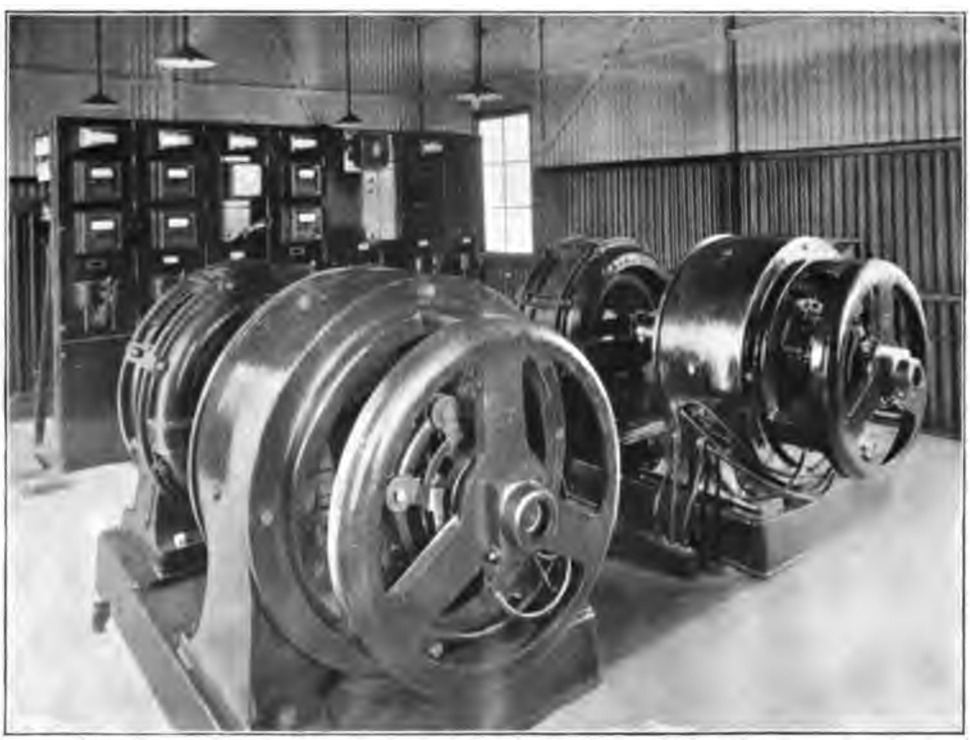


FIG. 240. DETAILS AND GENERAL VIEW OF 6-POLE, 50-KILOWATT, 525-VOLT, 725 REVOLUTIONS, CONTINUOUS-CURRENT GENERATOR FOR THE SUB-STATIONS OF THE YORKSHIRE POWER COMPANY

Width of tooth + slot at periphery...	0.68
„ „ + „ bottom of slot	0.606
Width of the slot as stamped	0.34
„ „ assembled	0.33
Number of slots...	95
„ „ per pole ...	15.83
Width of tooth at periphery, as stamped	0.34
Minimum width of tooth, „	0.278
Average „ „ „	0.309
Radial depth of the laminations	8.75
„ „ „ below slots ...	6.79
Number of ventilating ducts	1
Width of the duct	0.375
Bar Winding:	
Height of uninsulated conductor	0.35
Width of „ „	0.06
Height of insulated conductor	0.37
Width of „ „	0.08
Thickness of the slot insulation—copper to iron	0.055
Cross section bare conductor, square inches	0.021
Amperes per conductor	50
„ per square inch ...	2380
Conductors per slot	6
Total copper cross section per slot ...	0.126
Width × depth of slot, square inches	0.324
"Space factor" of slot	0.39
Magnet Core:	
Length of the pole face parallel to the shaft ...	6.5
Diameter of the bore of the pole face	20.58
Mean length of the pole arc	7.5
Ratio of pole arc to pitch	0.695
Radial length of the magnet core ...	7.3
Width of the magnet core parallel to the shaft	6.5
„ „ „ at right angles to the shaft ...	4.625
Radial depth of the air gap	0.165
Distance between pole tips	6.6
Yoke:	
External diameter	41.75
Internal „	35.75
Thickness of yoke	6.0
Axial width ...	150
Commutator:	
Diameter	15.0
Circumference ...	47.2
Number of segments	284
Thickness of segment + insulation at periphery	0.166
Useful depth of a segment	0.75
Total length of a segment ...	4.0

Brushes:

Number of sets	6
„ per set	2
Width of the brushes	1.25
Length of the arc of contact	0.5
Contact surface per brush, square inches	0.625
Material of the brushes	Carbon

ELECTRICAL AND MAGNETIC DATA

Armature:

Total induced voltage, full load	548
Terminal „ „	525
No load voltage	500
Number of face conductors	570
„ slots	95
„ conductors per slot	6
Arrangement of the conductors in the slot	2 × 3
Total amperes from commutator	100
Number of circuits	2
Amperes per circuit as dynamo	50
Total number of parallel paths through the winding	2
Number of conductors in series between brushes	284

Winding:

Mean length of a single turn, inches	52.5
Total number of turns (one dead coil)	285
Number of turns in series between brushes	142
Total length of conducting path between brushes, inches	7460
Cross section of one conductor, square inches	0.021
„ all parallel conductors	0.042
Specific resistance at 60 deg. Cent.	0.000000846
Resistance of winding from + to − at 60 deg. Cent.	0.15
C R loss in armature at 60 deg. Cent., volts	15
„ in the series spools at 60 deg. Cent., volts	4.5
„ „ brush contact surfaces, volts	2.0
Further C R Loss, volts	1.5
Total internal C R loss, volts	23

Commutation:

Diameter of the commutator	15
Periphery „ „	47.2
Revolutions per second	12.08
Peripheral speed in inches per second (= A)	570
Length of the arc of contact (= b), inches	0.5
Frequency of commutation (cycles per second) $\left(= \frac{A}{2b} = n\right)$	570
Width of a segment at the periphery (including insulation)	0.166
Maximum number of coils short-circuited under a brush	3.0
Turns per coil (q)	1

Maximum number of simultaneously-commutated conductors per group (r) ...	6.0
Lines per ampere turn per inch of gross core length ...	20
Total lines linked with short-circuited coil per ampere...	910
Inductance per segment (= henrys) ...	0.0000091
Reactance ,, ohm ($2 \pi nl$) ...	0.033
Reactance voltage, volts ...	1.6

MAGNETIC CIRCUIT

Flux entering armature per pole, no load, megalines (750 revolutions per minute) ...	2.36
Corresponding voltage ...	500
Flux entering armature per pole, full load, megalines (727 revolutions per minute) ...	2.66
Corresponding internal voltage ...	548
,, terminal ,, ...	525
Leakage factor ...	1.2
Flux generated per pole, no load, megalines ...	2.83
,, ,, full load ,, ...	3.2

Armature :

Cross-section of the core, square inches ...	44.14
Density, no load, c.g.s. lines ...	53,500
Density, full load ,, ...	59,200
Ampere turns per inch, no load ...	7.5
,, ,, full load ...	10
Magnetic length per pole, inches ...	6
Ampere turns, no load ...	45
,, full load ...	60

Teeth :

Number of teeth per pole...	15.8
Number of teeth directly below a mean pole arc ...	11.2
Percentage increase allowed for spread ...	10
Total number of flux-carrying teeth per pole ...	12.1
Cross-section of one tooth at root, square inches ...	1.55
Total cross-section at the bottom of these teeth, square inches ...	18.8
Apparent density, no load, c.g.s. lines ...	12,600
,, full load ,, ...	14,200
Mean width of tooth, inches ,, ...	0.31
Width of slot, inches ...	0.33
Mean width of tooth ÷ width of slot ...	0.94
Corrected density, no load, c.g.s. lines ...	12,200
,, full load ,, ...	13,200
Ampere turns per inch, no load ...	510
,, ,, full load ...	990
Length, inches ...	0.98
Ampere turns, no load ...	500
,, full load ...	970

Air Gap:

Cross-section at pole-face, square inches	48.0
Density at pole-face, no load, c.g.s. lines	49,000
„ „ full load „	55,500
Length of air gap, iron to iron, inches	0.165
Ampere turns, no load	2560
„ full load	2880

Magnet Core:

Cross-section, square inches	29.0
Density, no load, c.g.s. lines	97,200
„ full load „	11,000
Ampere turns per inch, no load	96
„ „ full load	152.5
Magnetic length, inches	7.25
Ampere turns, no load	695
„ full load	1110

Yoke:

Cross-section (magnetic), square inches	84
Density, no load, c.g.s. lines	34,000
„ full load „	38,000
Ampere turns per inch, no load	68.5
„ „ full load	84
Magnetic length per pole, inches	11
Ampere turns, no load	760
„ full load	930

Ampere Turns per Spool for No Load Voltage of 500:

Armature core	45
„ teeth	500
Air gap	2560
Magnet core	695
Yoke	760
Total number of ampere turns per spool, no load	4560
Corresponding speed	750 R.P.M.

Ampere Turns per Spool for Full Load Voltage of 525, *but no Load:*

Armature core	60
„ teeth	970
Air gap	2880
Magnet core	1110
Yoke	930
Total number of ampere turns per spool; full load voltage but no load	5950
Corresponding speed	725 R.P.M

Armature Interference

Armature ampere turns per pole	2380
Percentage brush shift, not stated but assumed = ...	5 per cent.
Percentage of demagnetizing turns	10
Demagnetizing ampere turns per pole	238
Distorting „ „	2142
Distortion factor $\left(\frac{F}{D}\right)$...	0.18

Summary

Ampere turns per field spool with no armature current, for uniform flux distribution (525 volts and 725 revolutions per minute)	5950
Ampere turns per pole to overcome armature demagnetization ...	238
„ „ „ „ distortion	386
Total ampere turns per pole, full load	6574
Calculated ampere turns per shunt spool, no load	4560
„ „ „ „ „ full load 4560 $\times \frac{525}{500}$...	4800
„ „ „ series „ „	1774
Actually allowed for in shunt spool...	5100
„ „ „ series „	2150

Shunt Winding

Mean length of one turn in feet	2.66
Ampere turns, full load	5,150
„ feet „	13,700
Total radiating surface per spool, square inches	221
Allow 0.54 watts per square inch.	
Watts in one shunt spool	120

Pounds of copper per spool $= 31 \dfrac{\frac{(\text{ampere feet})^2}{1000}}{\text{watts}} = \dfrac{31 \times 188}{120} = 48.5$ lb.

Volts in rheostat	100
„ 6 spools	400
„ 1 spool	66.5
Amperes per spool $\frac{120}{66.5}$	1.8
Turns per spool $\frac{5150}{1.8}$	2860
Length of wire in feet	7600
Pounds per 1000 ft.	6.4

Number 17 B. and S. gauge weighs 6.2 lb. per 1000 ft.

Watts in 6 shunt spools	720
„ shunt rheostat	180
Total watts in shunt circuit ...	900

Series Winding

Ampere turns (series), full load	2150
Total amperes of the machine, full load	100
Amperes in the series diverter rheostat	—
,, ,, winding	100
Turns per spool (series)	21.5
Dimensions of the conductor, inches	1.0 × 0.075
Number in parallel	—
Total cross-section, square inches	0.075
Amperes per square inch	1333
Mean length of turn, inches	31.95
Total length of conductor per series spool	686
Resistance per spool at 60 deg. Cent.	0.00766
Watts lost ,, ,, ...	76.6
Cylindrical surface, square inches	48.3
Watts lost per square inch at 60 deg. Cent.	1.6
Resistance of all series spools ,, ...	0.046
Watts lost in ,, ,, ...	460
Weight of copper per series spool, pounds	17
Total weight of series copper ,, ...	102

Armature Losses

Armature Copper Loss:

Resistance of the winding from + to − at 60 deg. Cent., ohms ...	0.15
Total amperes from commutator	100
Watts lost in armature copper at 60 deg. Cent.	1500

Core Loss:

Total core loss (observed), watts	2400

Friction Losses:

Bearing and air friction, watts	300

Armature Temperature Increase

Armature copper loss	1500
,, iron loss	2400
Total armature loss	3900
Circumference	63.5
Axial length of the winding, inches...	15
Peripheral surface, square inches	950
Watts per square inch of peripheral surface	4.1
Number of ventilating ducts	1
Total temperature increase by thermometer (observed)... ...	32 deg. Cent.

Commutator Losses

Length of brush contact arc, inches	0.5
Width of brush, inches	1.25
Contact surface per brush, square inches	0.625
Number of brushes per pole	2

Total number of positive brushes	6
Contact surface of all positive brushes, square inches	3.76
Current strength of the machine, amperes	100
Amperes per square inch of brush contact surface	26.6
Voltage drop at brush contacts, positive plus negative... ...	1.66
Total I^2R loss at brush contacts, watts	166
„ contact surface of brushes, positive plus negative ...	7.5
Brush pressure, pounds per square inch	1.3
Total brush pressure, pounds	9.8
Friction coefficient	0.25
Effective component of brush pressure, pounds	2.44
Diameter of commutator, inches	15
Revolutions per second	12.1
Peripheral speed of commutator in feet per second	47.5
Brush friction loss in watts per ampere	3.2
„ „ „	320
Total commutator loss, watts	486

Commutator Temperature Increase

Total commutator loss, watts	486
Circumference, inches	47.2
Length of commutator surface, inches	4.0
Cylindrical surface of commutator, square inches	190
Watts per square inch of cylindrical surface	2.52
Total temperature increase at the peripheral surface	28 deg. Cent.

Efficiency at 60 Deg. Cent.

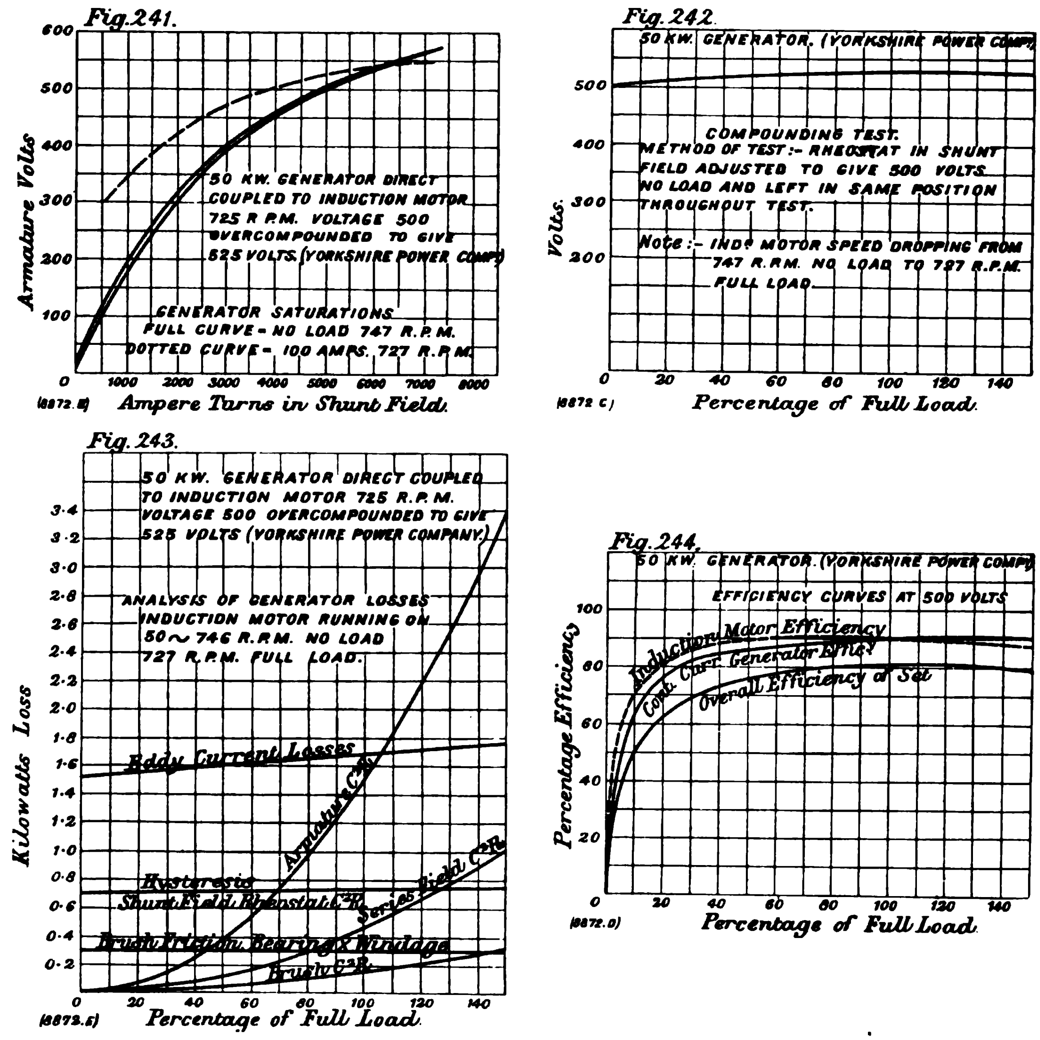
Iron loss, watts	2400
Watts lost in armature copper	1500
„ at the brush contact resistant at the commutator ...	166
Brush friction loss at the commutator	320
Friction loss at bearings and air friction	300
Watts lost in shunt winding	720
„ series „	460
„ shunt rheostat	180
Total of all losses	6046

Output at full load, watts...	50,000
Input „ „	56,046
Commercial efficiency at full load	89.6
Efficiencies deduced from tests :—	per cent.
At $\frac{1}{4}$ full load	80.0
„ $\frac{1}{2}$ „	86.5
„ $\frac{3}{4}$ „	89.0
„ „	90.0
„ $1\frac{1}{4}$ „	90.5

MATERIAL

Armature :

Core	Wrought-iron laminations
Spider	Cast iron
Conductors	Copper
Binding bands on the core	Steel wire
Binding bands over the end connections	,,



FIGS. 241 TO 244. TEST RESULTS FOR SATURATION, COMPOUNDING, LOSSES AND EFFICIENCY

Commutator :

Segments	Copper
Connections to the winding	,,
Spider and clamp rings	Cast iron

Insulation between segments	Reconstructed mica
„ on spider and clamp rings	„ „
Pole shoes	Wrought-iron laminations
Magnet cores	Do. do. do.
„ yoke	Cast iron

Test results for saturation, compounding, losses and efficiency, are given in the curves in Figs. 241 to 244, page 250.

On the occasion of the tests on this machine, the following notes were made :—

Operation

The commutation of this machine under all its tests was excellent.

As compound-wound generator:

On 530 *Volts*—

25 per cent. overload was carried with practically no sparking.
50 per cent. overload was carried with slight sparking.
100 per cent. overload was carried without serious sparking.

On 500 *Volts*—

25 per cent. overload was carried with very slight sparking.
75 per cent. overload was carried without serious sparking.

On 450 *Volts*—

25 per cent. overload was carried with slight sparking.
60 per cent. overload was carried without serious sparking.

Saturation

Sufficient margin is allowed in the field coils to reach 550 volts full load if necessary at any time.

Table LIII.—Log of Full Load Heat Run of 6-Pole, 50-Kilowatt, 525-Volt, 725 Revolutions Per Minute, Continuous-Current Generator

Time.	Armature Voltage.	Armature Current.	Field. Current.	Speed in R.P.M.	Temperature During Run in Deg. Cent.		Temperature of Air in Deg. Cent.	Remarks.
					Field.	Frame.		
10.40	500	100	1.25	725	22.2	18.7	18.4	Commutation good throughout.
11.10	„	„	„	„	35.3	20.0	18.8	
11.40	„	„	„	„	41.8	22.0	19.0	
12.00	„	„	„	„	45.0	23.5	19.0	
1.0	„	„	„	„	53.8	27.3	19.1	
2.0	„	„	„	„	57.0	30.3	19.2	
3.0	„	„	„	„	59.5	31.9	18.9	
4.0	„	„	„	„	61.1	32.5	18.4	
5.0	„	„	„	„	62.0	32.7	18.2	

Temperatures in deg. Cent. after six hours run, by thermometer:

	Final.	Rise.
Armature core	50	32
Commutator	46	28
Spools, shunt	55	37
Frame	33	15
Air	18	—

Resistances:

	Cold.	Hot.
Shunt Field.	245 volts.	334 volts.
	1.25 amperes.	1.50 amperes.
	196 ohms.	223 ohms.
	Per cent. increase, 13.8.	Rise, 34 deg. Cent.

Date of tests, February 14th and 15th, 1905.

TABLE LIV.—OVERALL EFFICIENCY TESTS

Input, A.C.							Output, D.C.					
							Field.		Armature.			
Volts.	Amperes.	Watts 1.	Watts 2.	Total.	Power Factor.	Per Centage of Load.	Amperes.	Volts.	Amperes.	Volts.	Watts.	Per Centage of Overall Efficiency.
2100	8.0	3,900	14,810	18,710	51.1	25	1.405	275	25	500	12,500	66.9
2100	10.7	10,780	22,400	33,180	85.3	50	1.345	259	50	500	25,000	75.4
2100	14.5	17,420	29,850	47,270	89.3	75	1.305	254	75	500	37,500	79.4
2100	19.0	24,900	36,300	61,200	88.5	100	1.300	250	100	500	50,000	81.65
2100	24.2	29,220	48,000	77,220	87.7	125	1.260	244	125	500	62,500	80.90
2100	30.0	34,220	60,100	94,320	86.5	150	1.300	250	150	500	75,000	79.50
2100	10.7	10,460	22,800	33,260	85.2	50	1.745	345	47.5	530	25,150	75.5
2100	19.0	24,600	36,450	61,050	89.5	100	1.53	310	95.0	530	50,300	82.4
2100	10.7	10,460	22,700	33,160	85.2	50	0.95	194	55.5	450	25,000	75.4
2100	19.0	23,400	39,150	62,550	90.4	100	0.91	175.5	111	450	50,000	80.0

Date of test, April 3rd, 1905.

DESIGNING COEFFICIENTS

The term "output coefficient," often denoted by the letter ϕ, appears to have been first suggested by Kapp and by Esson. Letting

D = diameter at air gap in centimetres

λg = the gross core length in centimetres

R.P.M. = the speed in revolutions per minute

and

K.W. = the kilowatts rated output

then

$$\phi = \frac{\text{K.W.}}{D^2 \times \lambda g \times \text{R.P.M.}}$$

The output coefficient is very useful to the designer. He knows the values attainable for given conditions, and strives in each case to obtain as high a value as is consistent with the specification to which the machine must comply. The cost for a given rating will generally be less the higher the output coefficient, though this need not necessarily be the case. Thus an increase in the output coefficient, obtained by disproportionate decrease in λg and increase in D, may even lead to an increase in cost. For the five multipolar continuous-current machines which have just been described, the output coefficients are set forth in Table LV.

TABLE LV

Machine.				D.		λg.		Output Coefficient ϕ
No. of Poles.	Kilowatts Rated Output	Speed in R.P.M.	Voltage.	In Inches.	In Centimetres.	In Inches.	In Centimeters.	
12	1500	75	{ 550, 600 }	126	320	33.75	85.7	0.00228
16	1000	90	500	138	350	13.8	35.1	0.00259
10	550	90	{ 500, 550 }	96	244	20.5	52.1	0.00197
6	250	320	{ 500, 550 }	46	117	12.3	31.2	0.00183
6	50	725	{ 500, 525 }	20¼	51.5	7.265	18.5	0.0014

One of the writers has put forward a proposition to define as "Specific Output" the output in watts per square centimetre of peripheral surface of the armature over the end connections of a "barrel-wound" armature, per revolution per minute.[1] Thus,

$$\text{"Specific Output"} = \frac{\text{K.W.}}{\pi \, \text{D L} \times \text{R.P.M.}}$$

where L is equal to the length of armature over end connections, the other terms having the same signification as in the "output coefficient" formula. Letting

$$\lambda g = \text{Gross length of armature core}$$
$$\tau = \text{Polar pitch at air gap,}$$

then it will be a fair approximation to substitute

$$\text{L} = \lambda g + 0.7\,\tau.$$

Then

$$\text{"Specific Output"} = \frac{\text{K.W.}}{\pi \, \text{D} (\lambda g + 0.7\,\tau) \times \text{R.P.M.}}$$

[1] *Electrician*, vol. 51, September 11th, 1903, pages 840 to 842.

This latter is the preferable form, owing to the diversity of arrangements of end connections which are nowadays employed.

The idea of the "specific output" was suggested by the chance discovery that the total works cost of continuous-current dynamos per square centimetre of peripheral surface of armature, *as measured from end to end of the armature winding*, is subject to comparatively slight variations. In other words, if we denote the total works cost in shillings by T.W.C., we have

$$\text{T.W.C.} = \text{K} \times \text{D} \times (\lambda g + 0.7\,\tau).$$

K will only vary extremely slowly with varying rated output, voltage and speed. As the result of a rather exhaustive study of this matter, it appears that machines of outputs varying from 100 kilowatts to 1000 kilowatts, and from 220 volts to 600 volts, and for all customary rated speeds for slow and high speed reciprocating engines, the values of K lie between 1.0 and 2.0. Of course, it varies considerably with the facilities, organisation, and scope of the manufacturing company, and on the cost of material and the cost and quality of labour in different countries.

PART II

ELECTRIC TRACTION MOTORS

ELECTRIC TRACTION MOTORS

MOTORS for electric traction must, from the nature of their work, be designed to be reversible, and to have the brushes set in a fixed position at a point midway between pole ends. Since the brushes cannot be shifted, the magnetic field cannot be utilised to reverse the current in the short-circuited coil; in fact, whatever impressed magnetic flux is passing through the coil while it is short-circuited under the brush, is in such a direction as to tend to maintain the current in its original direction, instead of assisting to reverse it. The commutation may be termed brush commutation, and the commutating element is in the resistance of the brushes. For satisfactory commutation, traction motors are designed with very high magnetisation at full load. Much higher densities are practicable as regards the heating limit, than in machines running at constant loads, since the average current input to a traction motor is not ordinarily above one-fourth of its rated capacity, so that in average work the magnetisation of the air gap and armature core is not very different from that in machines designed for constant load. At rated capacity, however, the magnetisation in the projections and armature core is frequently 50 per cent. higher than in machines designed for constant load, and at rated load the heat guaranteed per square inch of radiating surface is generally more than double that of machines for constant load.

Because of the unfavourable commutating conditions, the armature reaction of railway motors and the reactance voltage of the short-circuited coil should be comparatively small at rated capacity. This is the more important on account of the desirability of lessening the diameter of the armature, so as to shorten the magnetic circuit and diminish the weight of the motor. Material progress has been made in this direction by putting three, four, or even five, coils in one slot, where in former practice but one, corresponding to one commutator bar, was placed in one slot. This is a condition which would be adverse to satisfactory commutation with reasonable heating, in large generators for constant load; but in the case

of railway motors, on account of the lesser number of projections and consequent less room occupied for insulation, the cross-section of the projections has been increased so that a higher magnetisation in the gap is permissible, under which condition sparking is diminished at heavy loads. A material advance has been made in efficiency at average loads, and in sparking, by greatly increasing the magnetisation of the armature core proper.

It may be fairly said that all efforts to improve commutation have been, first, to increase magnetisation, so that distortion is diminished; and secondly, to diminish the inductance of the armature coils by employing open and wider slots. Machines have been constructed of 300 and 400 horse-power capacity, capable of being reversed in either direction without much sparking. That the commutation is never so perfect as in the case of machines where the reversing field can be utilised, is shown by the gradual roughening of the commutator, which requires more attention than in the case of generators or other non-reversible machines. The remarkable progress that has been made in the design of this class of machinery will be apparent by comparing the drawings and constants of well-known types of machines with those of machines constructed but a few years ago.

Description of a Geared Railway Motor for a Rated Drawbar Pull of 800 lb. at a Speed of 11.4 Miles per Hour

This motor has been in extensive use for some years, hence it does not represent the latest developments, except in so far as modifications have been introduced from time to time. The fundamental design, however, is not in accordance with the best examples of recent practice. On account of its established reputation for reliability, it is still, however, built in large numbers. Its constants are set forth below, in specification form, and in Figs. 245 to 254, pages 259, 261, and 265, are given drawings of the motor.

Specification

Number of poles...	4
Rated drawbar pull	800 lb.

Under standard conditions at this rating, the field windings are

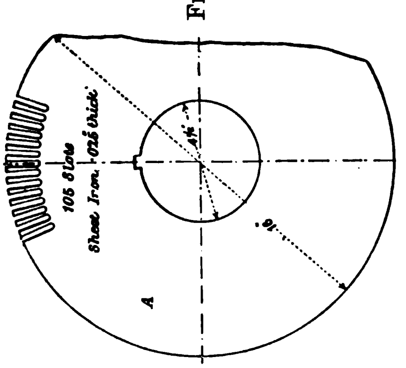


Fig. 245

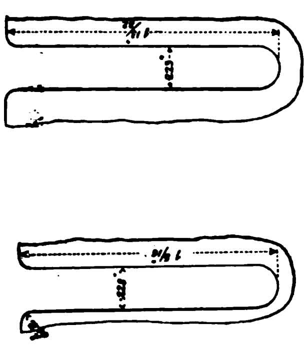


Fig. 246

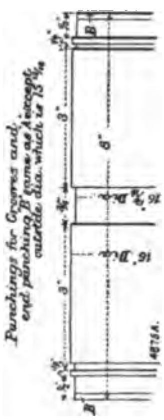


Fig. 247

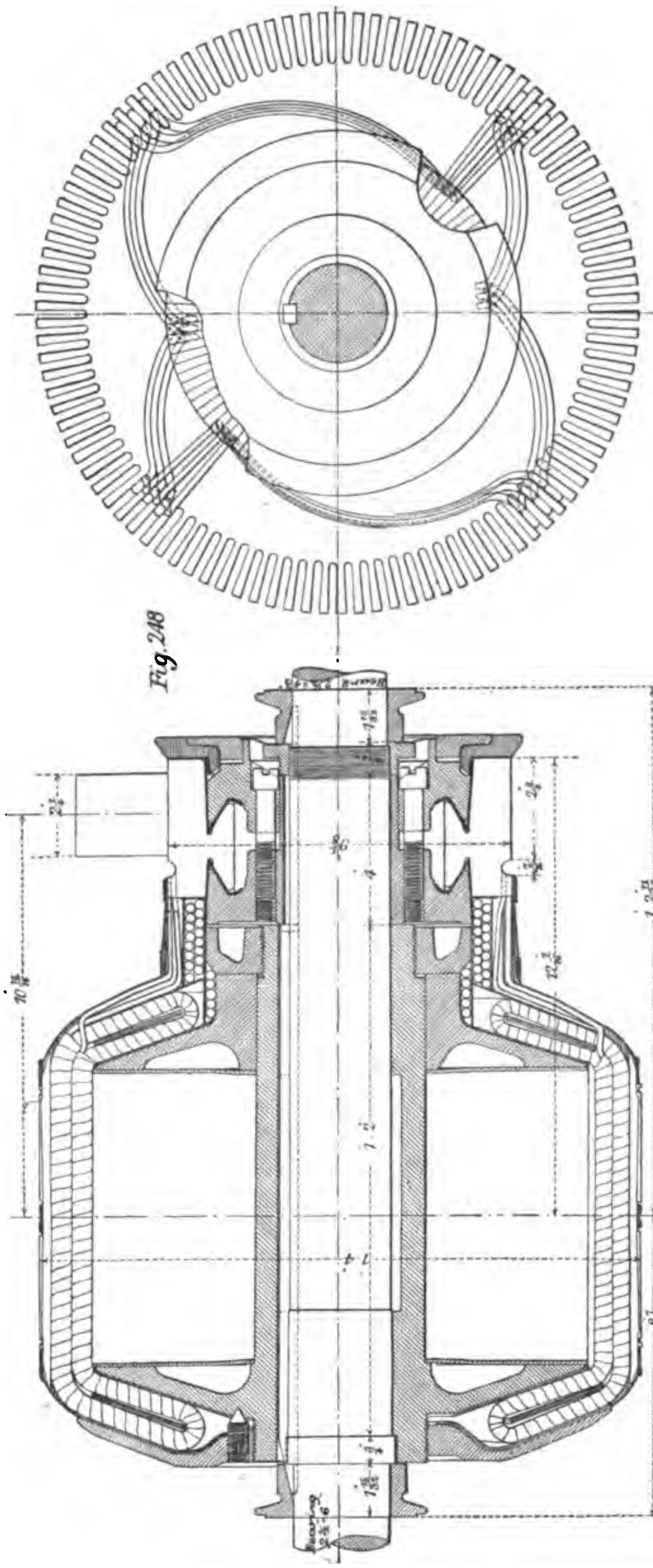


Fig. 248

Figs. 245 to 248. Armature of Geared Railway Motor for a Rated Draw-bar Pull of 800 lb., at a Speed of 11.4 Miles per Hour

connected in parallel with an external shunt which diverts from the field winding, 30 per cent. of the total current.

Revolutions of armature per minute at this rating	555
Number of teeth on armature pinion	14
„ „ axle gear	67
Ratio of gear reduction	4.78
Revolutions of axle per minute	116
Speed of car in feet per minute on 33-in. wheels	1000
„ miles per hour	11.4
Foot-pounds per minute, output for above drawbar pull and speed	800,000
Horse-power output for above drawbar pull and speed	24.2
Kilowatts output for above drawbar pull and speed	18.1
Efficiency of above rating, motor warm	79.5 per cent.
Corresponding kilowatts input	22.8
„ amperes „	45.5
Terminal voltage	500
Frequency in cycles per second at rated conditions	18.5

Dimensions

Armature:

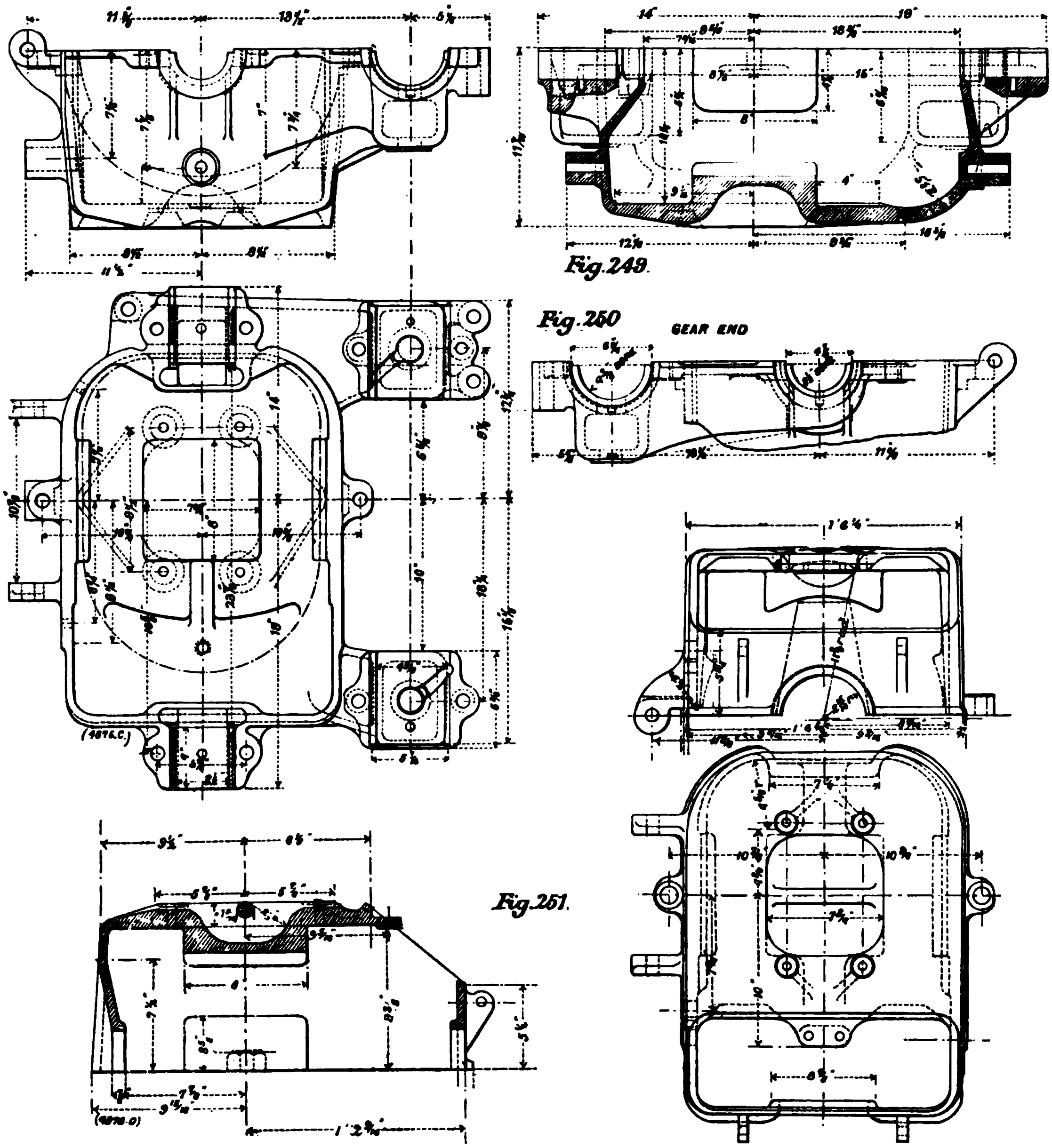
Diameter over all	16 in.
„ at bottom of slots	13.2 „
Internal diameter of core	$4\frac{1}{2}$ „
Length of core over all	8 „
Effective length, magnetic iron	7.2 „
Pitch at armature surface...	12.6 „
Japan insulation between laminations	10 per cent.
Thickness of laminations	0.025 in.
Depth of slot	1.40 „
Width of slot at root, die punch	0.240 „
„ „ surface, die punch	0.240 „
Number of slots	105
Minimum width of tooth	0.164 in.
Width of tooth at armature face	0.239 „
Size of armature conductor, B. and S. gauge	No. 9
Bare diameter of armature conductor	0.114 in.
Cross-section	0.0102 square inch

Magnet Core:

Length of pole face	8 in.
„ arc	8.25 „
Pole arc ÷ pitch	0.655 „
Length of magnet core	8 „
Width „ „	7.75 „
Diameter of bore of field	$16\frac{9}{32}$ „
Length of gap clearance above armature	$\frac{1}{8}$ „
„ „ below „	$\frac{5}{32}$ „

Commutator :

Diameter	$8\frac{1}{2}$ in.
Number of segments	105
" " per slot	1



Figs. 249 to 251. Details of Railway Motor Construction

Width of segment at commutator face	0.214 in.
" " root	0.128 "
Thickness of mica insulation	0.04 "
Available length of surface of segment	$3\frac{3}{4}$ "

Brushes:

Number of sets	2
„ of brushes in one set	1
Length, radial	$2\frac{3}{8}$ in.
Width	$2\frac{1}{4}$ „
Thickness	0.5 „
Area of contact of one brush	1.125 square inches
Type of brush	radial carbon

TECHNICAL DATA

Terminal voltage	500
Number of face conductors	840
Conductors per slot	8
„ coil	4
Number of circuits	2
Style of winding	Single
Gramme ring or drum	Drum
Type of construction of winding	Formed coil winding
Number of coils	105
Mean length of one armature turn	43 in.
Total armature turns	420
Turns in series between brushes	210
Length between brushes	9000 in.
Cross-section of one armature conductor	0.0102 square inch
Ohms per cubic inch at 20 deg. Cent.	0.00000068 ohms.
Resistance between brushes at 20 deg. Cent.	0.305 „
„ „ 95 „	0.394 „
Volts of drop in armature at 95 deg. Cent.	18
Mean length of one field turn	46.5 in.
Field conductor, B. and S. gauge	No. 6
Bare diameter	0.162 in.
Cross-section of field conductor	0.0205 square inch
Turns per field spool	203
Number of field spools	2
Total field turns in series	406
„ length of spool copper	18.800 in.
„ resistance of spool winding at 20 deg. Cent.	0.625 ohm.
„ „ „ 95 „	0.81 „
Thirty per cent. of the main current of 45.5 amperes is diverted from the field winding by a suitable shunt resistance, hence current in field winding is	32 amperes
Volts drop in field winding at 95 deg. Cent.	26 volts
Resistance brush contacts (positive *plus* negative)	0.055 ohm
Volts drop in brush contacts	2.5 volts
„ armature, field, and brushes	46.5 „
Counter electromotive force of motor	453.5 „
Amperes per square inch in armature winding	2230
„ „ field	1560

Commutation :

Average voltage between commutator segments	18
Armature turns per pole	105
Amperes per turn	22.8
Armature ampere turns per pole	2400
Frequency of commutation (cycles per second)	250
Number of coils simultaneously short-circuited per brush ...	3
Turns per coil	4
Number of conductors per group simultaneously undergoing commutation	24
Flux per ampere turn per inch length of armature lamination ...	20
„ linked with 24 turns with one ampere in those turns $= 20 \times 8 \times 42 =$	3840
Inductance of four turns $= 4 \times 3480 \times 10^{-8} =$	0.000154 henrys

But in a two-circuit winding with four poles and only two sets of brushes, there are two such four-turn coils in series, being commutated under one brush, and their inductance is $= 2 \times 0.000154 = 0.000308$ henrys.

Reactance of these two short-circuited coils	.484 ohm
Amperes in short-circuited coils	22.8
Reactance voltage of short-circuited coils	11 volts

MAGNETOMOTIVE FORCE

Megalines entering armature, per pole-piece	2.92
Coefficient of magnetic leakage	1.25
Megalines per field-pole	3.65

Armature :

Section	62.8 square inches
Density	46.5 kilols.
Length (magnetic path)	4 in.
Ampere turns per inch of length	8
„ for armature core	30

Teeth :

Transmitting flux from one pole-piece	19
Section at roots	22.5 square inches
Length	1.4 in.
Apparent density at root tooth	130 kilols.
Corrected „ „	125 „
Ampere turns per inch of length	700
„ for teeth	980

Gap :

Section at pole-face	66 square inches
Length, average of top and bottom	0.14 in.
Density at pole-face	44 kilols.
Ampere turns for gap	1920

Cast-Steel Portion of Circuit:

Average cross-section	... 52 square inches
Length, magnetic	... 9 in.
Average density	... 70 kilols.
Ampere turns per inch of length	... 35
„ for cast-steel frame, per pole-piece ...	... 320

Only two of the four poles carry exciting windings; hence of the 203 turns on one spool, only 101.5 are to be taken as corresponding to one pole-piece. Thirty per cent. of the main current being diverted from the fields, the field exciting current is 32 amperes, and field ampere turns per pole-piece are $32 \times 101.5 = 3250$ ampere turns. These are probably distributed somewhat as follows:

Ampere turns for armature core	30
„ „ teeth	980
„ „ gap	1920
„ „ frame	320
Total ampere turns per pole-piece ...	3250

THERMAL CONSTANTS

Armature:

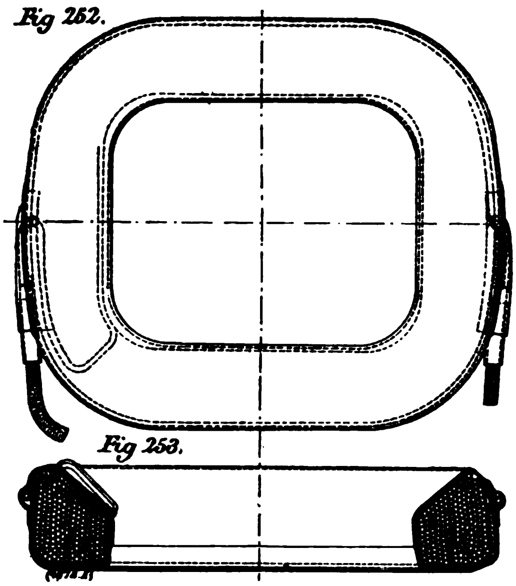
Resistance between brushes at 95 deg. Cent.	... 0.394 ohm
Amperes input at rated capacity	... 45.5 amperes
Armature C^2R loss at 95 deg. Cent.	... 815 watts
Total weight of armature laminations, including teeth ...	... 314 lb.
„ observed core loss (only apparently core loss) ...	... 800 watts
Watts per pound in armature laminations	... 2.55 „
Total of armature losses	... 1615 „
Length of armature (over conductors)	... 12 in.
Peripheral radiating surface of armature	... 600 square inches
Watts per square inch peripheral radiating surface ...	... 2.7 watts

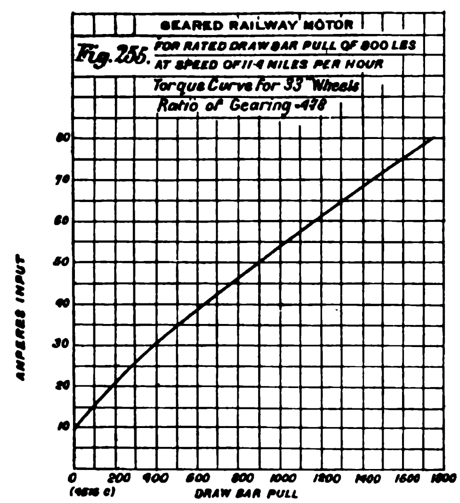
Field Spools:

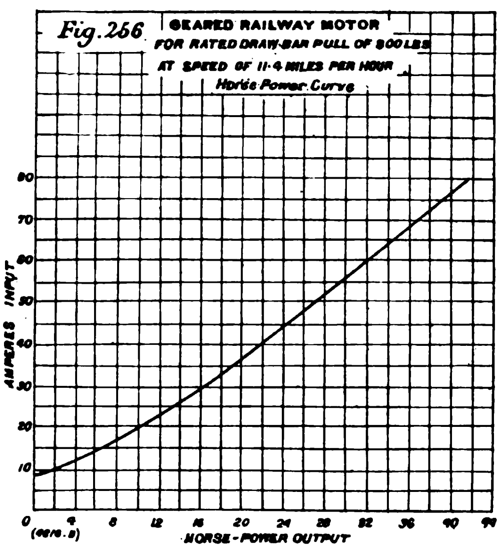
Total resistance of the two field spools at 95 deg. Cent.	... 0.81 ohm
Amperes in spool winding	... 32 amperes
Spool C^2R loss at 95 deg. Cent.	... 830 watts

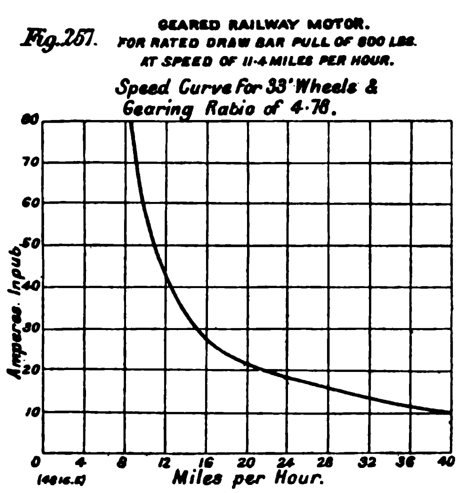
Commutator:

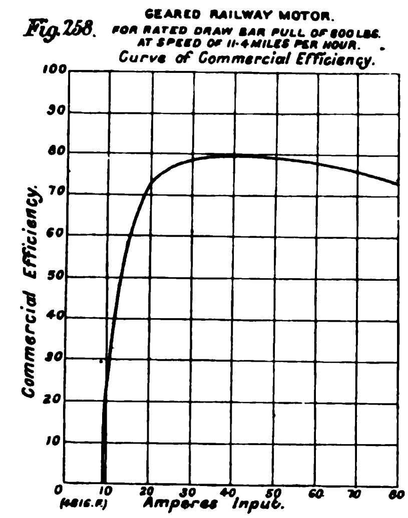
Area of bearing surface of positive brush	... 1.13 square inches
Amperes per square inch of brush-bearing surface ...	... 40 amperes
Ohms per square inch of bearing surface of carbon brushes	... 0.03 ohm
Brush resistance, positive + negative	... 0.053 „
Volts drop at brush contacts	... 2.4 volts
C^2R at brush contacts	... 110 watts
Brush pressure per square inch	... 2 lb.
Total brush pressure	... 4.5 „











FIGS. 252 TO 258. FIELD COIL AND DIAGRAMS OF GEARED RAILWAY MOTOR

Coefficient of friction	0.3
Peripheral speed of commutator in feet per minute	1240
Brush friction	36 watts
Stray power lost in commutator (allowance)	50 „
Total commutator loss	198 „
Peripheral radiating surface	100 square inches
Watts per square inch radiating surface of commutator ...	2 watts

Efficiency Calculations

	Watts.
Output at rated capacity	18,100
Core loss	800
Commutator and brush loss	198
Armature C^2 R loss at 95 deg. Cent.	815
Field spool C^2 R „ „	830
Gearing friction...	2,000
Total input	22,743

Commercial efficiency at rated capacity and 95 deg. Cent. = 79.5 per cent.[1]

Weights

	lb.
Armature core (magnetic)	250
„ teeth	67
„ copper	60
Commutator bars	45
Armature complete	635
Magnetic pole	520
Spool copper	129
Machine complete	1525

In Figs. 255 to 258, page 265, are given respectively curves of drawbar pull, output, speed, and efficiency for this motor.

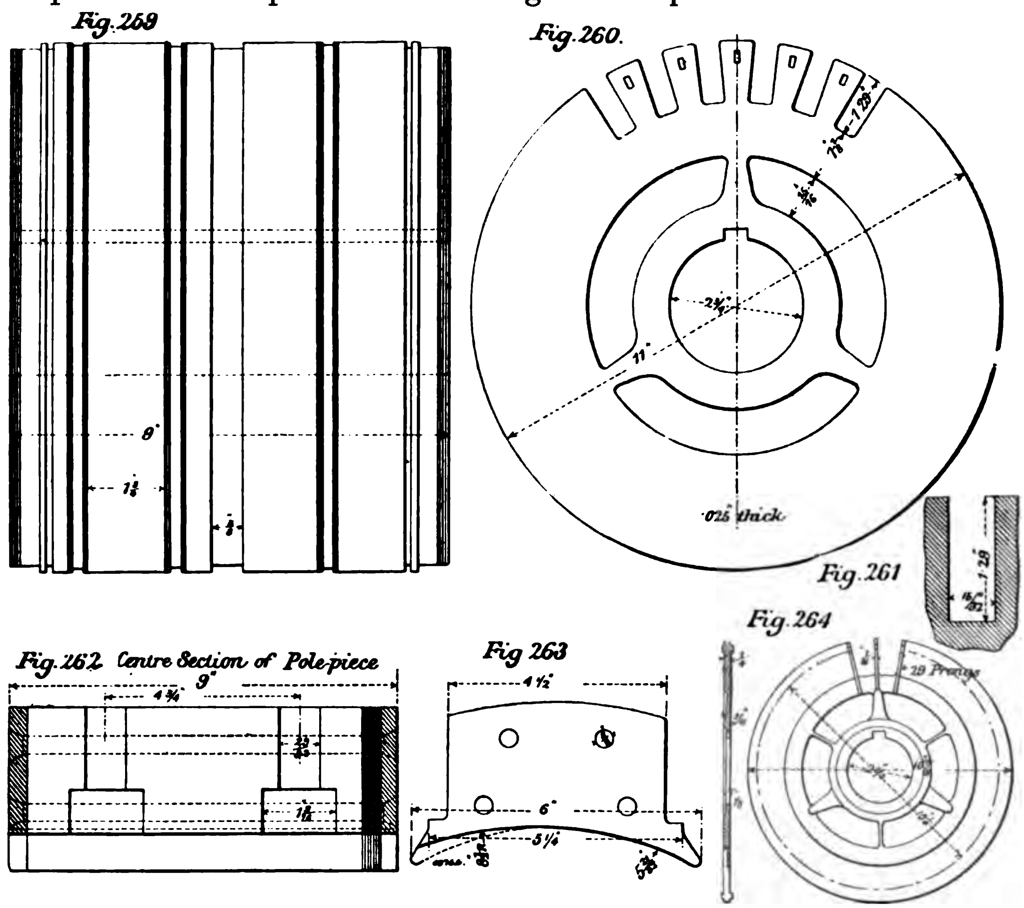
In many of the more modern street-railway motors, the design has followed lines differing in many respects from those of the motor just described. Thus several armature coils are arranged in one slot, largely reducing the number of slots, and the pole-faces are laminated, since otherwise these few wide slots would set up too great an eddy-current loss in the pole-face. It has been found preferable to have one field spool per pole-piece, instead of having two salient and two consequent poles. The armature diameter has been largely reduced, and sparking is minimised by running not only the teeth, but also the core, up to extremely high magnetic density; nevertheless, owing to the greatly reduced mass of the

[1] In this result, the loss in the diverting shunt to the field spool winding is not allowed for.

armature iron, the core loss is small. A motor designed on these lines, and of not very different capacity from the one just described, will next be reviewed.

Geared Railway Motor for a Rated Output of 27 Horse-Power at an Armature Speed of 640 Revolutions per Minute

The rating of this motor is in accordance with the now generally-accepted standard practice of limiting the temperature rise of field and

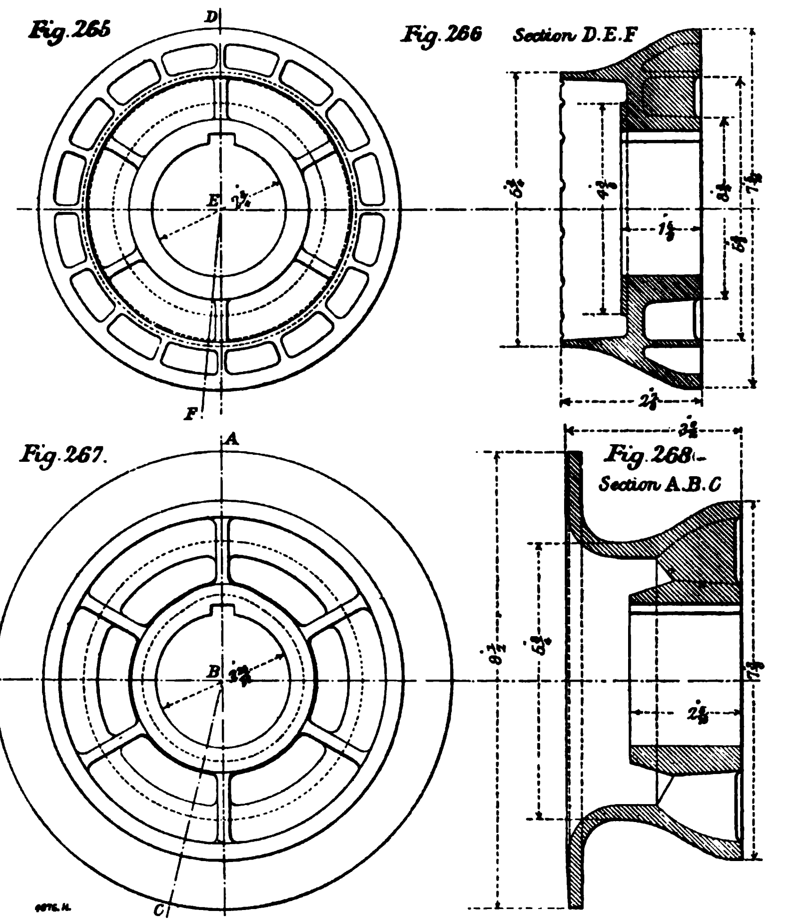


Figs. 259 to 264. Details of 27 Horse-Power Geared Railway Motor. Armature Speed, 640 Revolutions per Minute

armature to 75 deg. Cent., as measured by thermometer after a full-load run of one hour's duration. The motor is illustrated in Figs. 259 to 277 inclusive (see above, and pages 268, 270, 272, 273, and 275).

Applying this same standard permissible temperature rise to runs of different durations, the corresponding ratings at 500 terminal volts are as follow :

Length of Run. Hours.	Amperes.	Horse-Power
½	75	38 2
1	51	27
1½	39.5	21 3
2	32.5	17.5
3	23.5	12 5
4	17	8.6
5	14.5	6.9
6	14	6.6



Figs. 265 to 268. Details of 27 Horse-Power Geared Railway Motor. Armature Speed, 640 Revolutions per Minute.

The following specification is prepared on the basis of the rating of 27 horse-power for one hour's continuous operation at full load. In tramway service, of course, the motor is on the average called upon to develop but a small percentage of its full capacity; and hence such a motor, when continuously in service under normal conditions, runs much cooler than the above-quoted temperatures.

SPECIFICATION

Number of poles	4
Rated horse-power output	27
„ kilowatts	20.2
Efficiency at above rating and at 95 deg. Cent.	79 per cent.

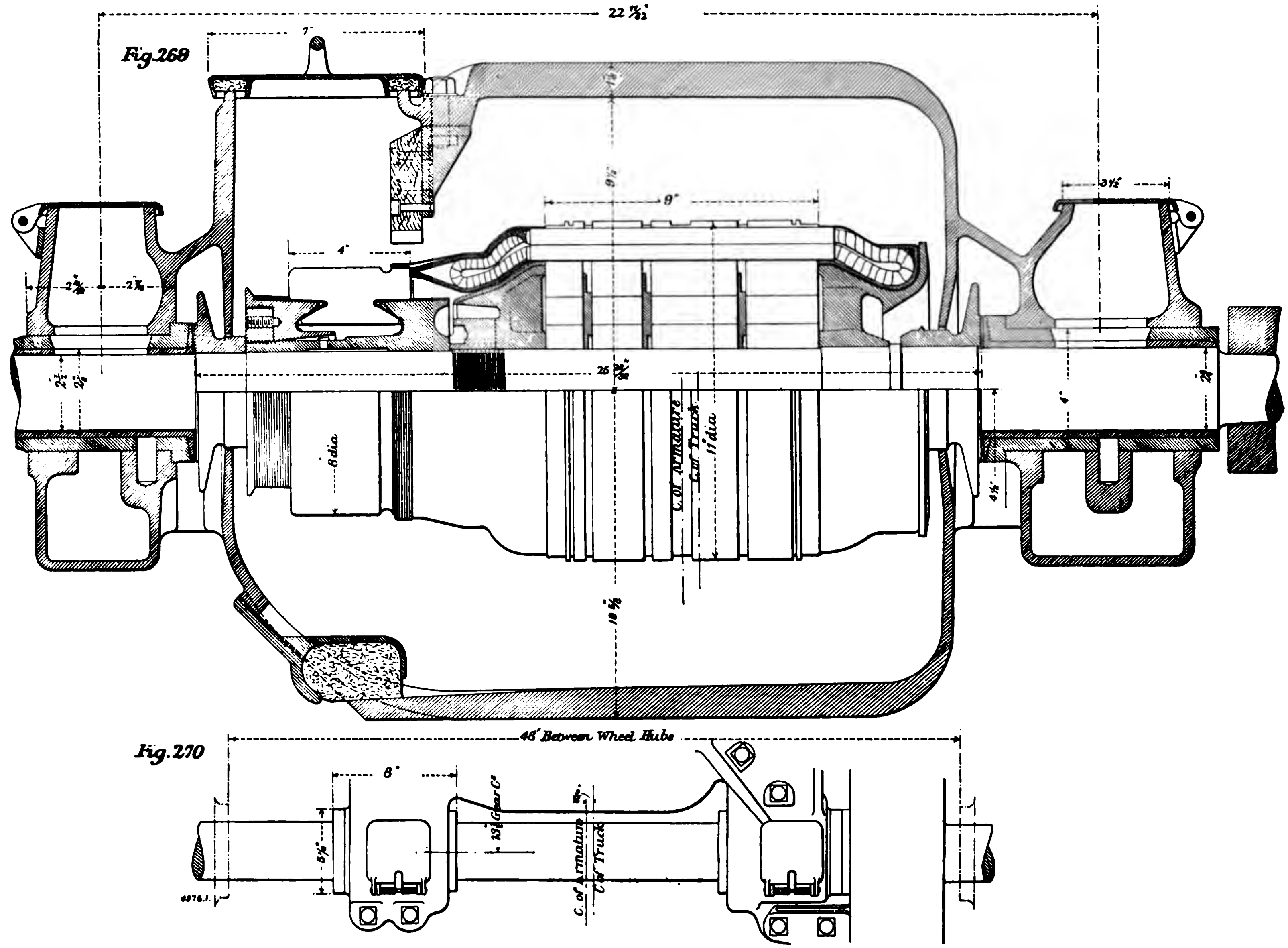
The efficiency is a little higher at lighter loads, and is at its maximum at about two-thirds full-rated load, so that it is high throughout the entire range of working, that is, from quarter-load to heavy overloads. (See efficiency curve in Fig. 282, page 276.)

Kilowatts input at rated load	25.6
Terminal voltage	500
Corresponding amperes input	51
„ revolutions per minute of armature	640
Number of teeth on armature pinion	14
„ „ axle gear	67
Ratio of gear reduction	4.78
Revolutions of axle per minute	134
Speed of car in feet per minute, on 33-in. wheels	1160
„ miles per hour „	13.1
Output in foot-pounds per minute, at normal rating	890,000
Pounds drawbar pull, at normal rating	770
Frequency at rated conditions in cycles per second	21.4

DIMENSIONS

Armature:

Diameter over all	11 in.
„ at bottom of slots	8.42 „
Internal diameter of useful magnetic portion of core	6.17 „
Length of core over all	9 „
Number of ventilating ducts, each $\frac{1}{4}$ in. wide	3
Effective length of magnetic iron	7.42 in.
Pitch at armature surface	8.65 „
Japan insulation between laminations	10 per cent.
Thickness of laminations	0.025 in.
Depth of slot	1.29 „
Width of slot at root	$\frac{15}{32}$ „
„ „ surface	$\frac{15}{32}$ „
Number of slots	29
Minimum width of tooth	0.445 in.
Width of tooth at armature face	0.724 „
Size of armature conductor, B. and S. gauge	No. 10
Bare diameter of armature conductors	0.102 in.
Cross-section „ „	.0081 square inches



Figs 269 and 270. 27 Horse-Power Geared Railway Motor. Armature Speed, 640 Revolutions per Minute

Magnet Core:

Length of pole-face	9 in.
„ arc	6.1 „
Pole arc ÷ pitch	0.69 „
Length of magnet core	$8\frac{7}{8}$ „
Width	$4\frac{3}{8}$ „
Diameter of bore of field	$11\frac{9}{32}$ „
Length of gap clearance above armature	$\frac{1}{8}$ „
„ „ below „	$\frac{5}{32}$ „

Commutator:

Diameter	8 in.
Number of segments	87
„ segments per slot	3
Width of segment at commutator face	0.243 in.
„ segment at root	0.108 „
Thickness of mica insulation	0.050 „
Available length of surface of segment	$2\frac{7}{8}$ „

Brushes:

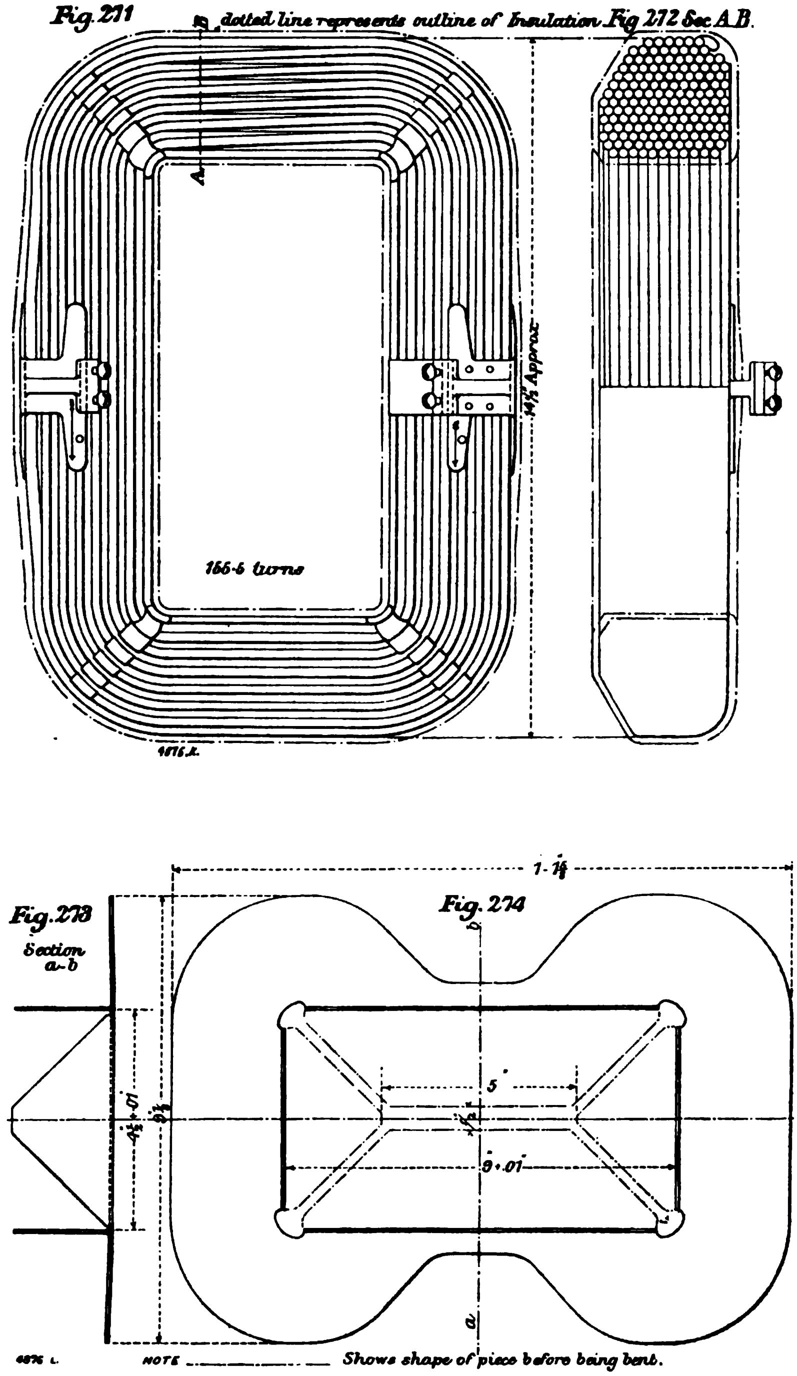
Number of sets	2
„ in one set	2
Length, radial	$2\frac{1}{4}$ in.
Width	$1\frac{1}{4}$ „
Thickness	$\frac{1}{2}$ „
Area of contact of one brush	625 square inches
Type of brush	Radial carbon

MATERIALS

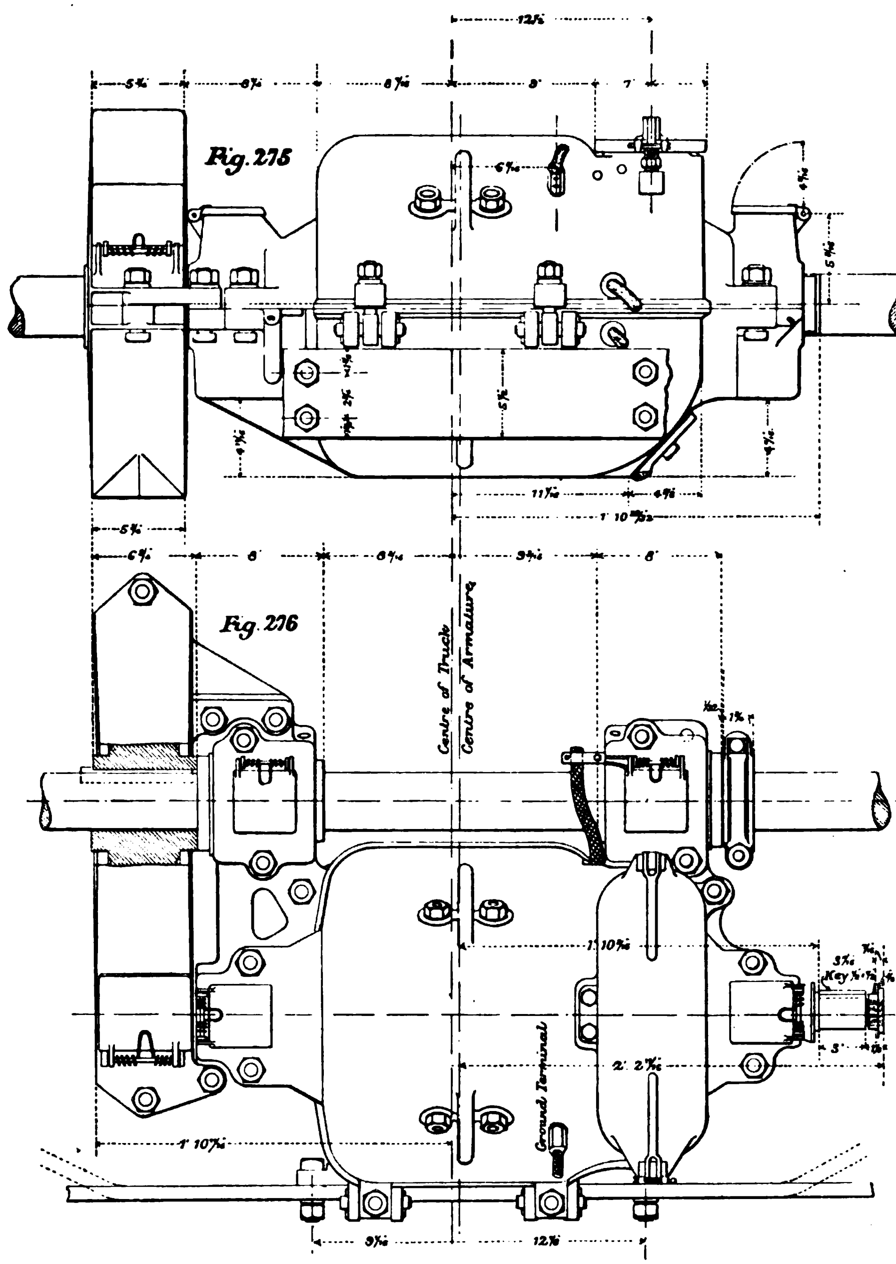
Armature core	Sheet steel
Magnet frame	Cast „
Pole-faces	Sheet „
Brushes	Carbon

TECHNICAL DATA

Terminal voltage	500
Number of face conductors	696
Conductors per slot	24
„ coil	4
Number of circuits	2
Style of winding	Single
Gramme ring or drum	Drum
Type construction of winding	Formed coil winding
Number of coils	87
Mean length of one armature turn	38.5 in.
Total armature turns	348
Turns in series between brushes	174
Length between brushes	6700 in.
Cross-section of one armature conductor	0.0081 square inch



Figs. 271 to 274. Field Coil of 27 Horse-Power Geared Railway Motor



FIGS. 275 AND 276. 27 HORSE-POWER GEARED RAILWAY MOTOR, ARMATURE SPEED, 640 REVOLUTIONS PER MINUTE

Ohms per cubic inch at 20 deg. Cent. ...	0.00000068
Resistance between brushes at 20 deg. Cent. ...	0.28 ohm
,, ,, ,, 95 ,,	0.36 ,,
Volts drop in armature at 95 deg. Cent.	18.3 volts
Mean length of one field turn	36 in.
Size of field conductor, B. and S. gauge	No. 5
Bare diameter ...	0.182 in.
Cross-section of field conductor	0.026 square inch
Turns per field spool	156.5
Number of field spools	4
Total field turns in series ...	626
,, length of spool copper	22,000 in.
,, resistance spool winding at 20 deg. Cent.	0.59 ohm
,, ,, ,, ,, 95 ,,	0.76 ,,
Volts drop in field winding at 95 ,,	38.6 volts
Resistance brush contacts (positive + negative)	0.048 ohm
Volts drop in brush contacts	2.4 volts
,, ,, armature, field, and brushes	59.3 ,,
Counter electromotive force of motor	441
Amperes per square inch in armature winding	3130
,, ,, ,, field ,,	1920
Commutation :	
Average voltage between commutator segments	21
Armature turns per pole ...	87
Amperes per turn	25.5
Armature ampere turns per pole ...	2200
Frequency of commutation, cycles per second	270
Number of coils simultaneously short-circuited, per brush	2
Turns per coil ...	4
Number of conductors per group, simultaneously undergoing commutation	16
Flux per ampere turn per inch-length of armature lamination ...	20 lines
,, linked with 16 turns with 1 ampere in those turns, $= 20 \times 9 \times 16$	2880 ,,
Inductance of four turns $= 4 \times 2880 \times 10^{-8}$	.000115 henrys
In a four-pole, two-circuit winding, and with only two sets of brushes, there are two such four-turn coils in series, being commutated under the brush, and their inductance is	0.000230 henrys
Reactance of these two short-circuited coils ...	0.39 ohm
Amperes in short-circuited coils	25.5 amperes
Reactance voltage of short-circuited coils	9.9 volts
Magnetomotive Force Estimations :	
Megalines entering armature, per pole-piece ...	2.96
Coefficient of magnetic leakage	1.25
Megalines per field pole...	3.70
Armature :	
Section	16.7 square inches
Density	177 kilols.

Fig. 277

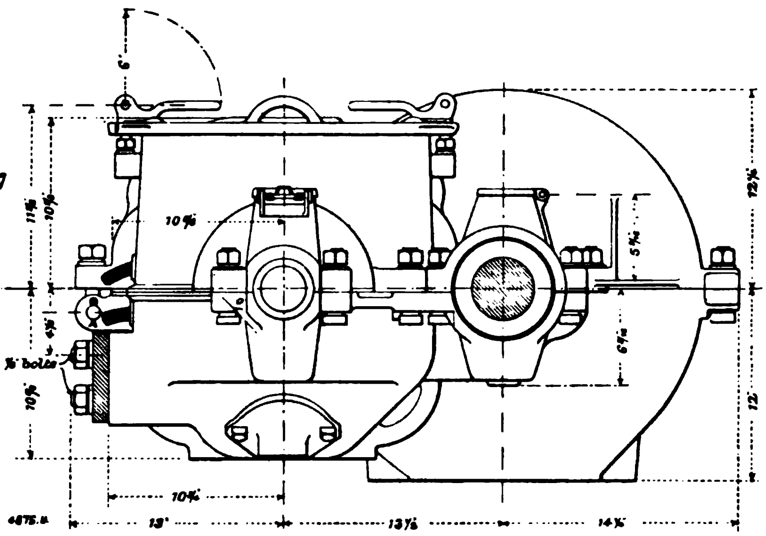


Fig. 278

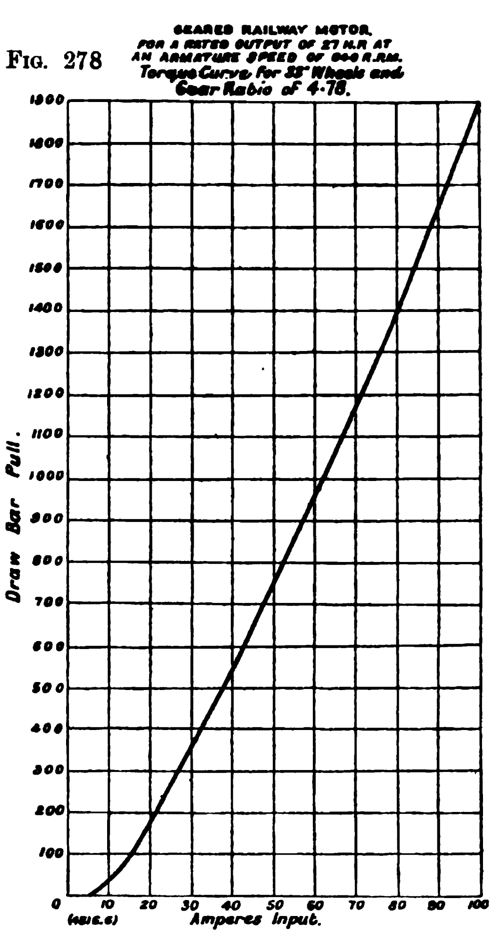
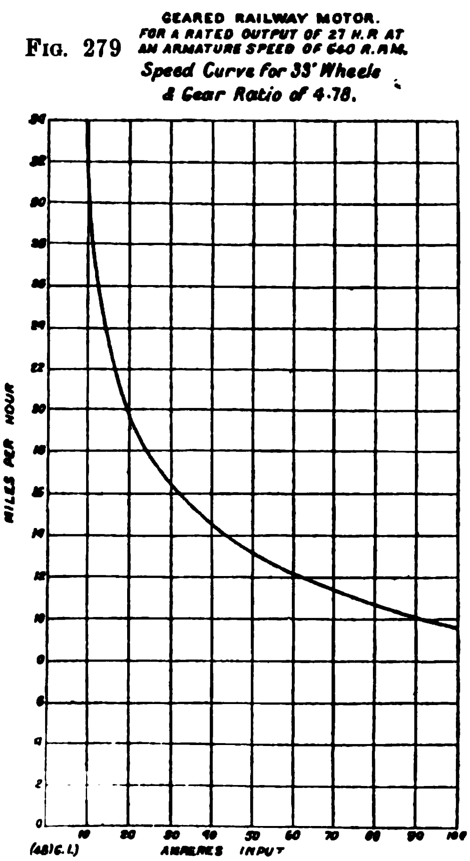
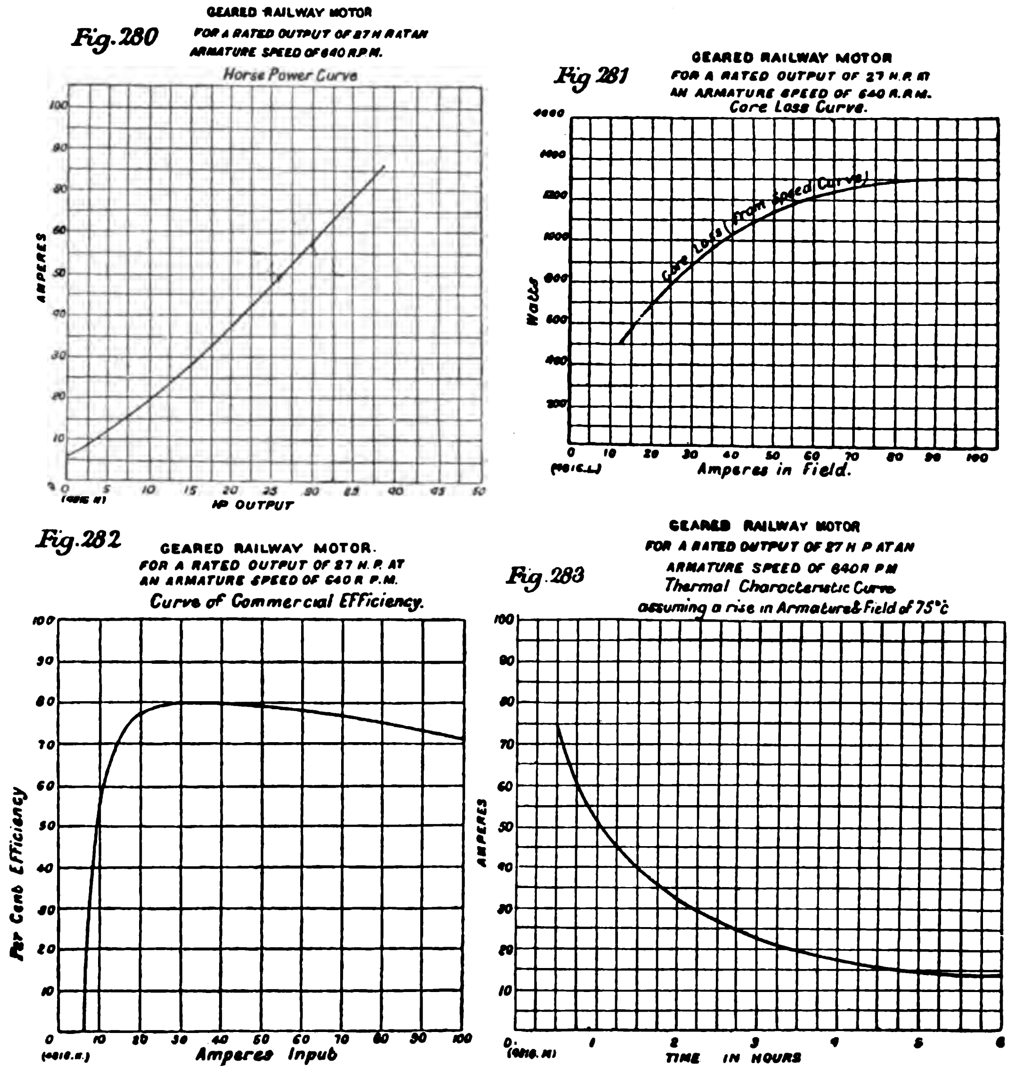


Fig. 279



Figs. 277 to 279. 27 Horse-Power Geared Railway Motor
Torque and Speed Curves

But, as is evident from the drawing of Fig. 260, page 267, many lines will flow through the inner parts of the punchings, and also, to a certain extent, through the shaft, and a corrected density may be taken of, say 130 kilolines.



FIGS. 280 TO 283. CHARACTERISTIC CURVES OF 27 HORSE-POWER GEARED RAILWAY MOTOR

Length (magnetic)	3 in.
Ampere turns per inch of length	900
„ for armature core	2700

Teeth :

Transmitting flux from one pole-piece	6
Section at root of six teeth	20 square inches

Length	1.29 in.
Apparent density in root tooth	148
Corrected " "	138
Ampere turns per inch of length	1300
" for teeth	1680

Gap:

Section at pole-face	55 square inches
But owing to the special method of constructing the pole-face (see Figs. 262 and 263), whereby the entire surface is not equally effective, a corrected section at pole-face should be taken, equal to, say	45 square inches
Mean length of air gap	0.14 in.
Pole-face density (from corrected section)	66 kilols.
Ampere-turns for gap	2900

Cast-Steel Portion of Circuit:

Average cross-section	39 square inches
Length (magnetic)	7.5 in.
Average density	96 kilols.
Ampere turns per inch of length	90
" for cast-steel frame per pole-piece	670

Each spool carries 156.6 turns, and in this motor full field is always used, *i.e.*, no portion of the main current is diverted through an auxiliary shunt. Hence

Ampere-turns per field spool at full rated load are equal to $156.5 \times 51 =$ 7950 ampere turns.

This magnetomotive force of 7950 ampere turns can be considered to be distributed somewhat in the following manner:

	Ampere Turns
Armature core	2700
Teeth	1680
Gap	2900
Steel Frame	670
Total magnetomotive force per pole-piece	7950

It is not intended to convey the impression that any high degree of accuracy is obtainable in these magnetomotive force estimations in railway motors; but working from the observed results, and from the known dimensions of the apparatus, and the assumed properties of the material employed, some rough idea of the distribution of the magnetomotive force is obtained.

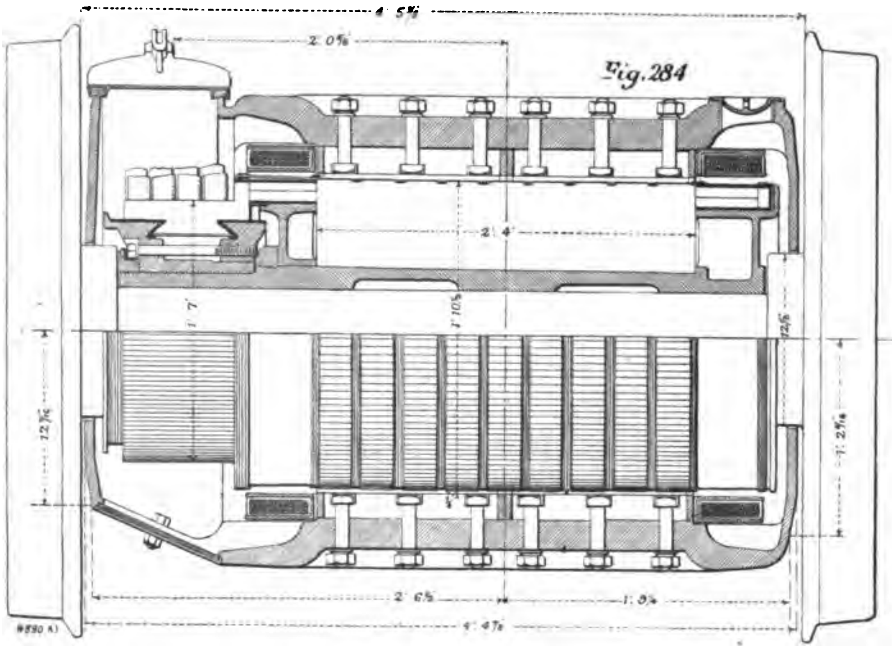


Fig. 284

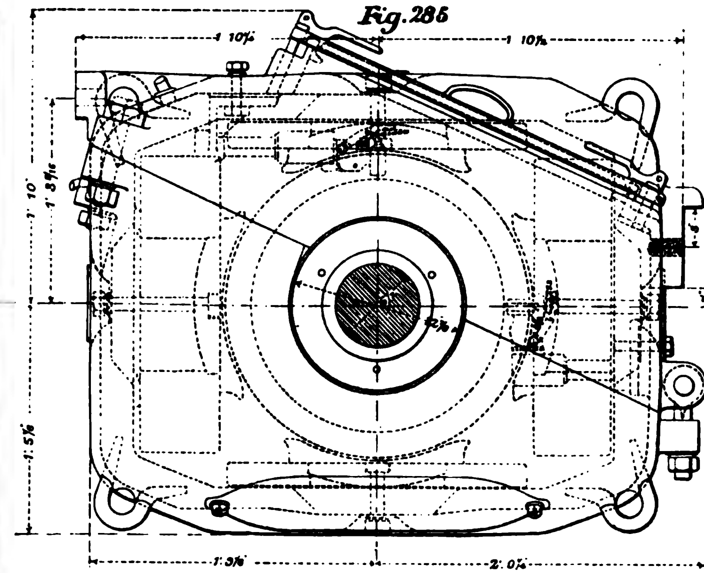


Fig. 285

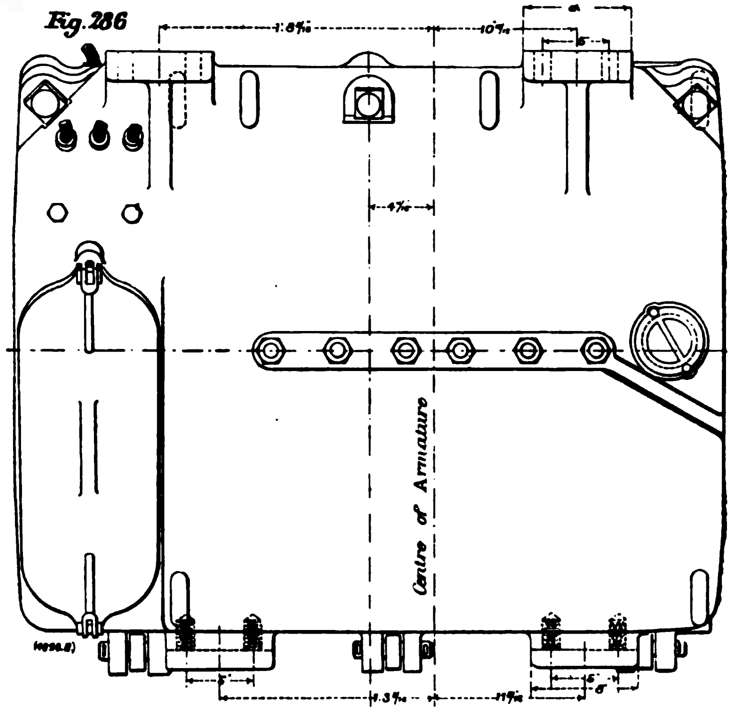


Fig. 286

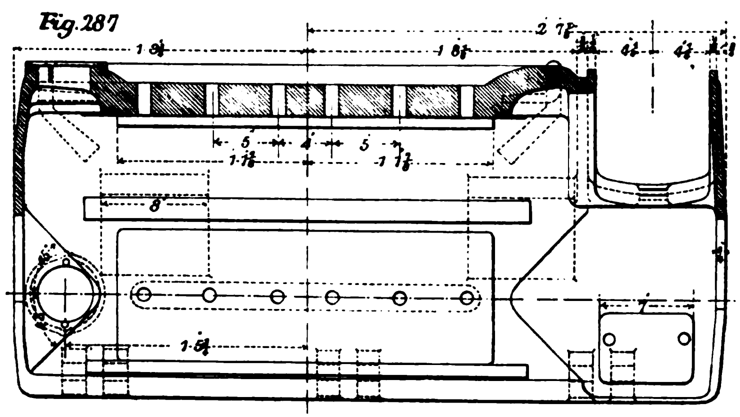


Fig. 287

FIGS. 284 TO 287. DIRECT CONNECTED RAILWAY MOTOR

Thermal Constants

Armature:

Resistance between brushes at 95 deg. Cent.	0.36 ohm
Amperes input at rated capacity	51 amperes
Armature C^2 R loss at 95 deg. Cent.	925 watts
Total weight of armature laminations, including teeth	120 lb.
„ observed core loss (only apparently core loss)	1120 watts
Watts per lb. in armature laminations	9.3 „
Total of armature losses	2045 „
Length of armature, over conductors	13.5 in.
Peripheral radiating surface of armature	465 square inches
Watts per square inch peripheral radiating surface	4.4 watts

Field Spools:

Total resistance, all field spools at 95 deg. Cent.	0.76 ohm
Current in spool winding	51 amperes
Spool C^2R loss at 95 deg. Cent.	2000 watts

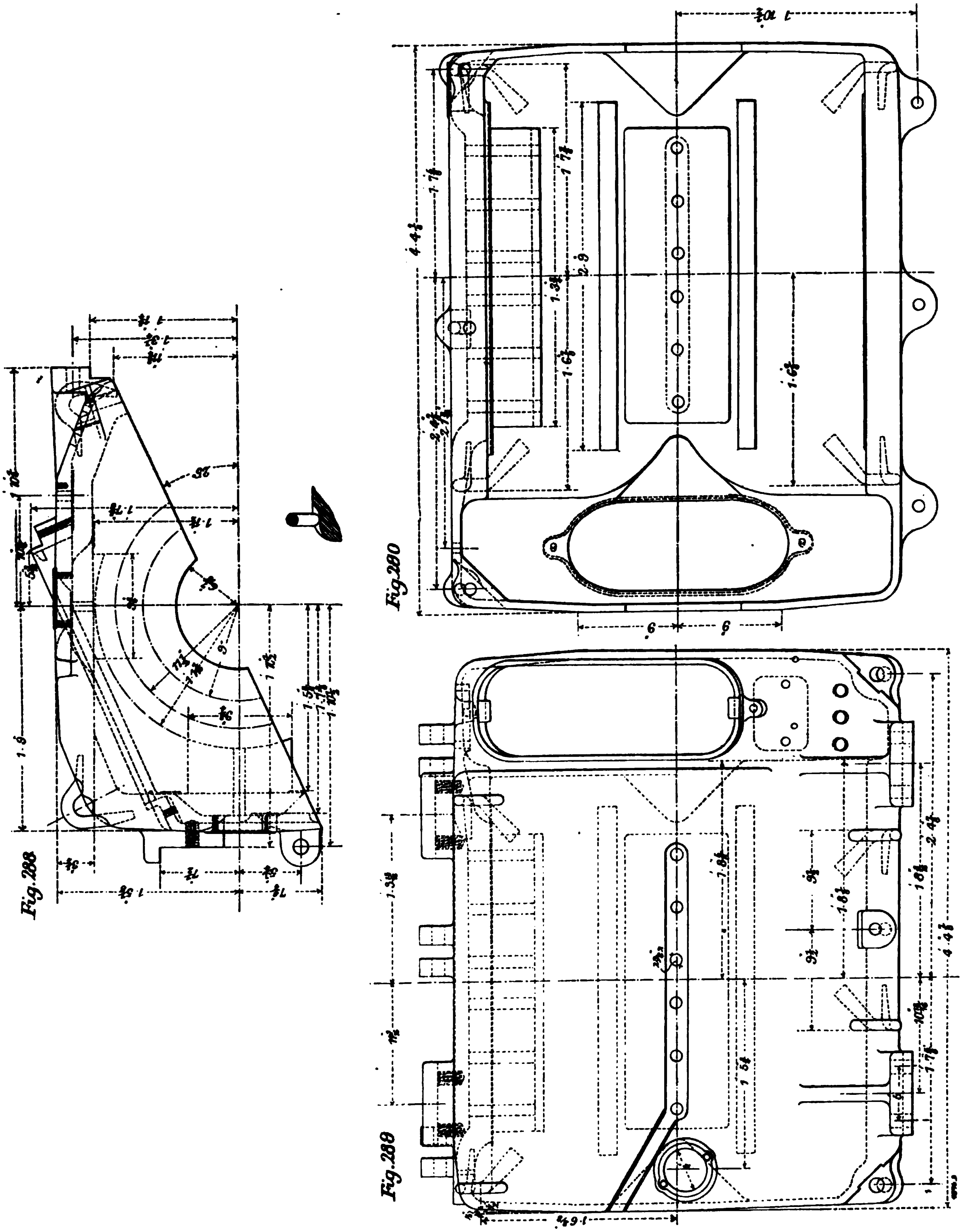
Commutator:

Area of bearing surface of positive brushes	1.25 square inches
Amperes per square inch of brush-bearing surface	40.5 amperes
Ohms per square inch of bearing surface of carbon brushes	0.03 ohm
Brush resistance, positive + negative	0.048 „
Volts drop at brush contacts	2.4 volts
C^2R at brush contacts (watts)	122 watts
Brush pressure, pounds per square inch	2 lb.
Total brush pressure	5 „
Coefficient of friction	0.3
Peripheral speed of commutator (feet per minute)	1850 ft.
Brush friction	46 watts
Allowance for stray power lost in commutator	50 „
Total commutator loss	216 „
Peripheral radiating surface	95 square inches
Watts per square inch peripheral radiating surface of commutator	2.3 watts

Efficiency Estimations

	Watts.
Output at rated capacity	20,200
Core loss	1,120
Commutator and brush loss	218
Armature C^2R loss at 95 deg. Cent.	925
Field „ „ „	2,000
Gearing friction	1,200
Total input	25,663

Commercial efficiency at rated capacity and 95 deg. Cent. = 79 per cent.



FIGS. 288 TO 290. DIRECT-CONNECTED RAILWAY MOTOR

WEIGHTS

	lb.
Armature laminations	= 120
„ complete (with pinion)	= 357
Motor complete (without axle gear and gear case)	= 1460

In Figs. 278 to 283, on pages 275 and 276, are given curves of D.P.B., speed, output, core loss, efficiency, and thermal characteristics.

DIRECT-CONNECTED RAILWAY MOTOR

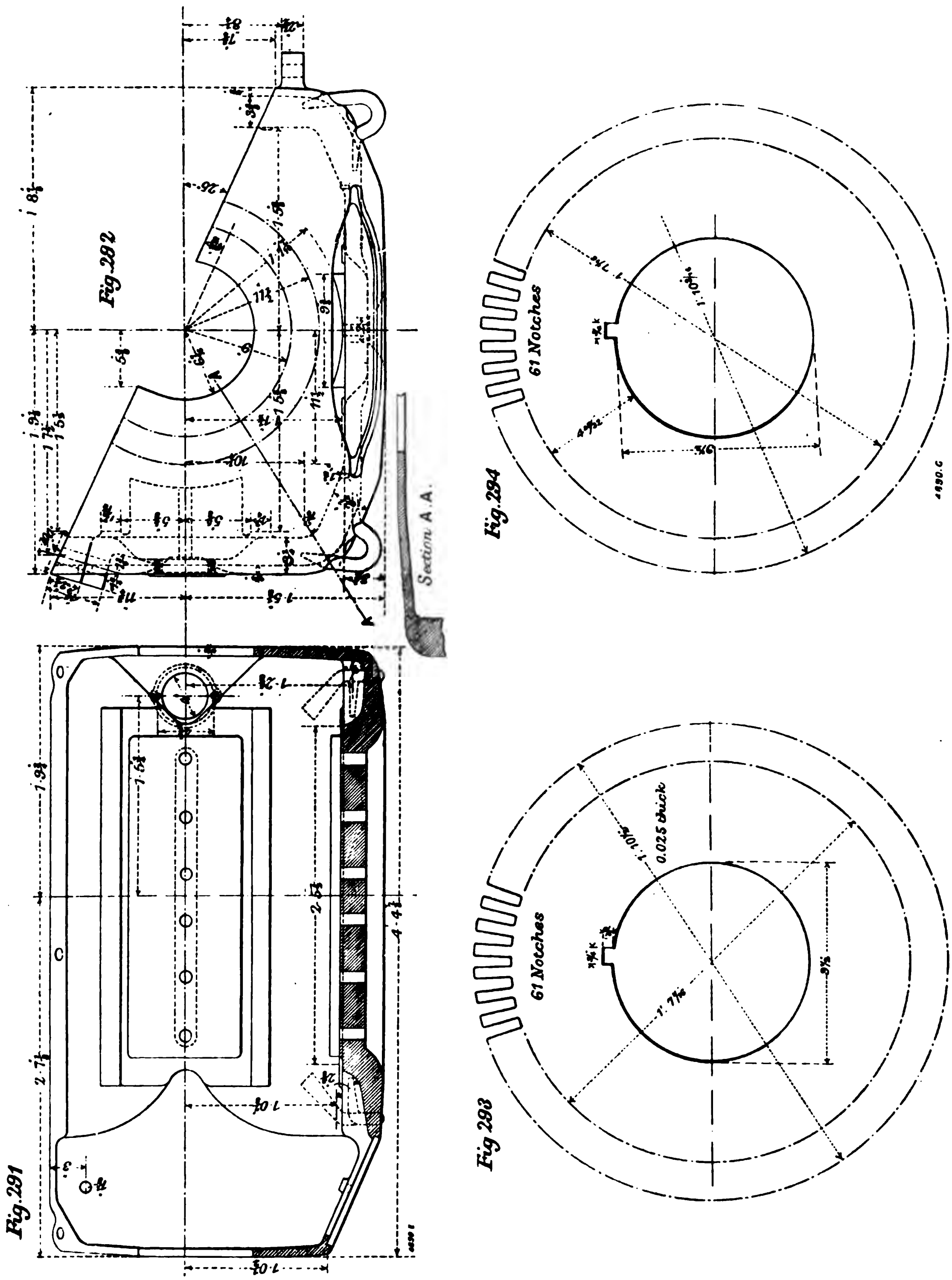
This motor gives an output of 117 horse-power, at a speed of 23.8 miles per hour on 42-in. wheels. It contributes 1840 lb. to the drawbar pull of the 35-ton locomotive, for the equipment of which four such motors are employed. Consequently, the total drawbar pull of this locomotive at the above speed is 7350 lb., but the motor is capable of exerting a torque far in excess of this figure; in fact, up to the limit of the tractive effort possible for a locomotive of this weight, before slipping takes place. Drawings for this motor are given in Figs. 284 to 319 (see pages 278 to 289), and its constants are set forth in the following:

Number of poles	4
Drawbar pull at 23.8 miles per hour	1840 lb.
Corresponding speed, miles per hour	23.8 miles
Speed in feet per minute	2100 ft.
Diameter of driving wheels	42 in.
Armature revolutions per minute	190
Output in foot-pounds per minute for above drawbar pull and speed	3,860,000
Ditto in horse-power	117
„ kilowatts	87.5
Corresponding kilowatts input	95.8
Terminal voltage	500 volts
Current input	192 amperes
Frequency in cycles per second	6.35 cycles

DIMENSIONS

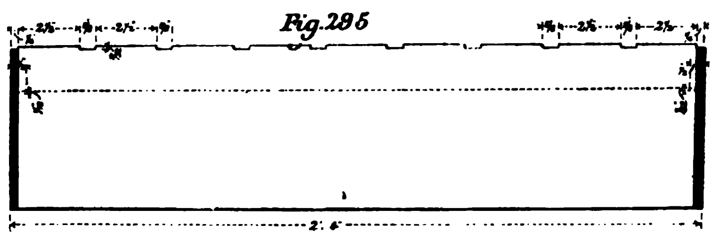
Armature:

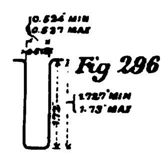
Diameter over all	$22\frac{1}{2}$ in.
Length over conductors	$45\frac{3}{4}$ „
Diameter at bottom of slots	19.04 „
Internal diameter of core	$9\frac{1}{2}$ „
Length of core over all	28 „
Effective length, magnetic iron	25.2 „
Pitch at armature surface...	17.7 „



FIGS. 291 TO 294. DIRECT-CONNECTED RAILWAY MOTOR

Japan insulation between laminations	10 per cent.
Thickness of laminations	0.025 in.
Depth of slot	1.73 ,,
Width ,, at root	0.52 ,,
,, ,, surface	0.52 ,,
Number of slots	61
Minimum width of tooth	0.463 in.
Width of tooth at armature face	0.635 ,,
,, conductor	0.10 ,,
Depth ,, ...	0.60 ,,
Apparent cross-section of armature conductor	0.060 square inch
This is a pressed stranded conductor, made up of 49 strands of No. 19 B. and S. guage. The cross-section of a No. 19 guage wire is 0.0101 square inch, hence the cross-section of the 49 strands is 49 × 0.0101	0.0495 square inch





Figs. 295 and 296. Cross-Section of Armature Core and Section of Slot for the 117 Horse-Power Railway Motor

But allowance must also be made for the increased resistance due to the increased length of the individual strands when twisted in the process of forming. Hence the equivalent cross-section of solid copper should be estimated at	0.046 square inch

This was the experimentally-determined value in this case, and is fairly representative of stranded conductors of about these dimensions.

Magnet Core:

Length of pole-face	28 in.
,, arc	13.2 ,,
Pole arc ÷ pitch	73 per cent.
Length of magnet core	28 in.
Width ,, ...	$9\frac{3}{4}$,,
Diameter of bore of field	$23\frac{1}{16}$,,
Length of gap clearance above armature	$\frac{5}{16}$,,
,, ,, below ,, ...	$\frac{1}{4}$,,

Commutator:

Diameter	19 ,,
Number of segments	183
,, ,, per slot	3

Width of segment at commutator face	0.286 in.
„ „ root	0.200 „
Thickness of mica insulation	0.04 „
Available length of surface of segment	8 „
Brushes:	
Number of sets	2
„ in one set	4
Length (radial)	2½ in.
Width	1¾ „
Thickness	$\frac{11}{16}$ „
Area of contact of one brush	1.2 square inch
Type of brush	Radial Carbon

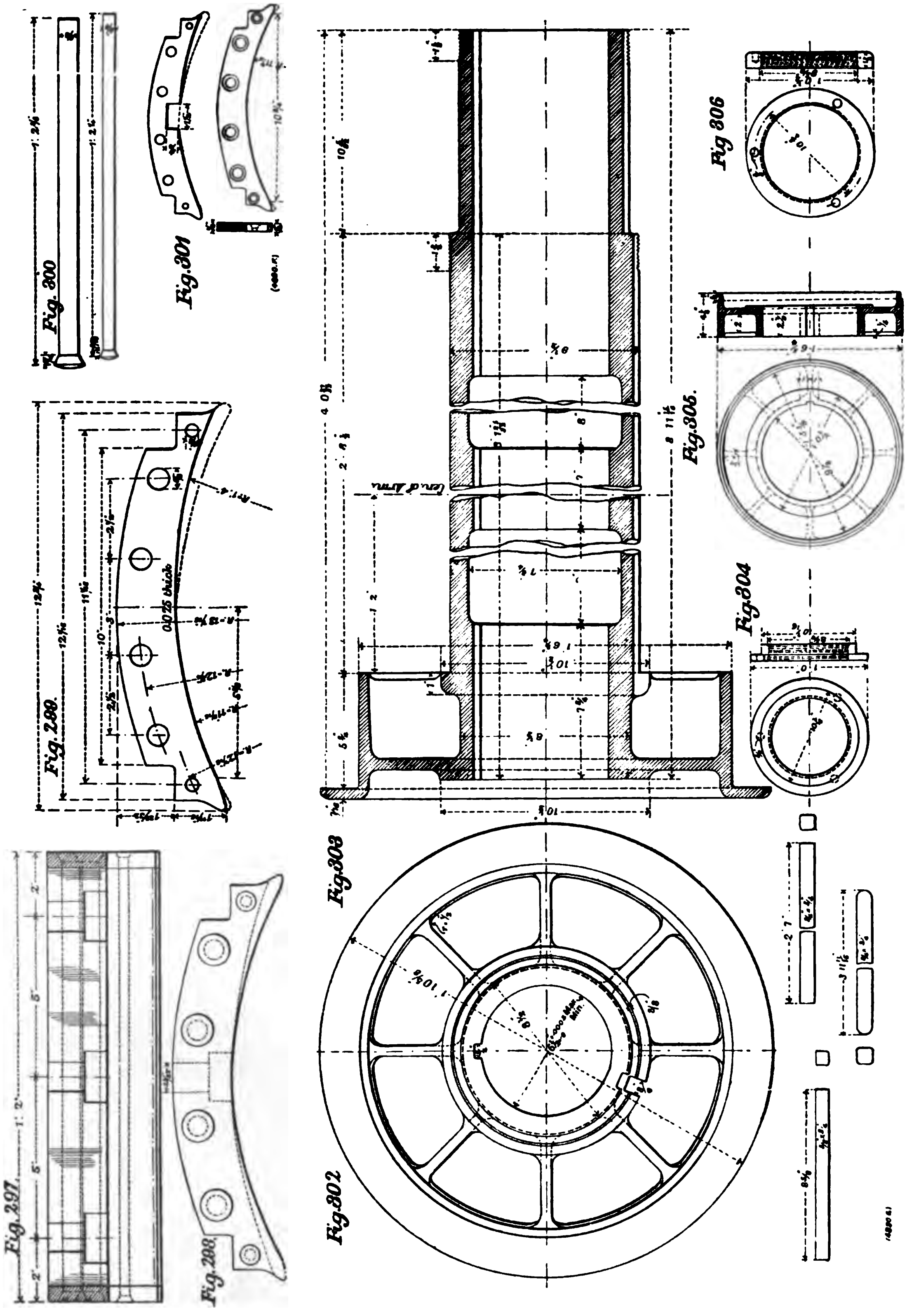
MATERIALS

Armature core	Sheet Steel
„ spider	No. 3 metal
„ flanges	Cast iron
„ conductors	Pressed stranded copper
Commutator segments	Copper
„ spider	Malleable cast iron
Pole-pieces	Sheet steel
Yoke and magnet cores	Cast „
Brushes	Carbon

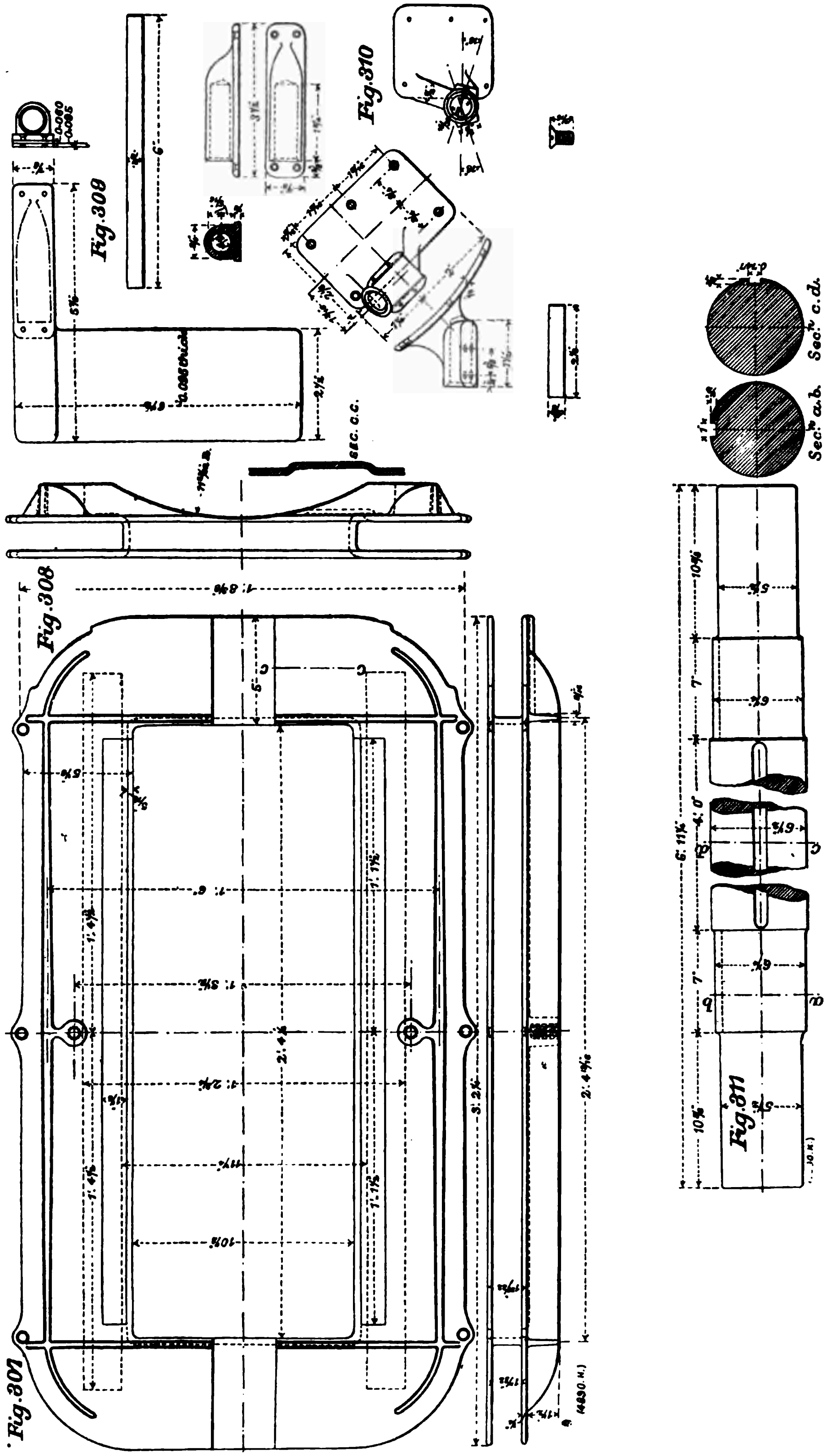
TECHNICAL DATA

Terminal voltage	500 volts
Number of face conductors	366
Conductors per slot	6
Number of circuits	2
Style winding	Single
Gramme ring or drum	Drum
Type construction of winding	Barrel-wound
Mean length of one armature turn	103 in.
Total armature turns	183
Turns in series between brushes	91
Length between brushes	9400 in.
Virtual cross-section of one armature conductor	0.046 square inch
Ohms per cubic inch at 20 deg. Cent.	0.00000068
Resistance between brushes at 20 deg. Cent.	0.070 ohms
„ „ „ 70 „	0.084 „
Volts drop in armature at 70 deg. Cent.	16 volts
Mean length of one field turn	95 in.

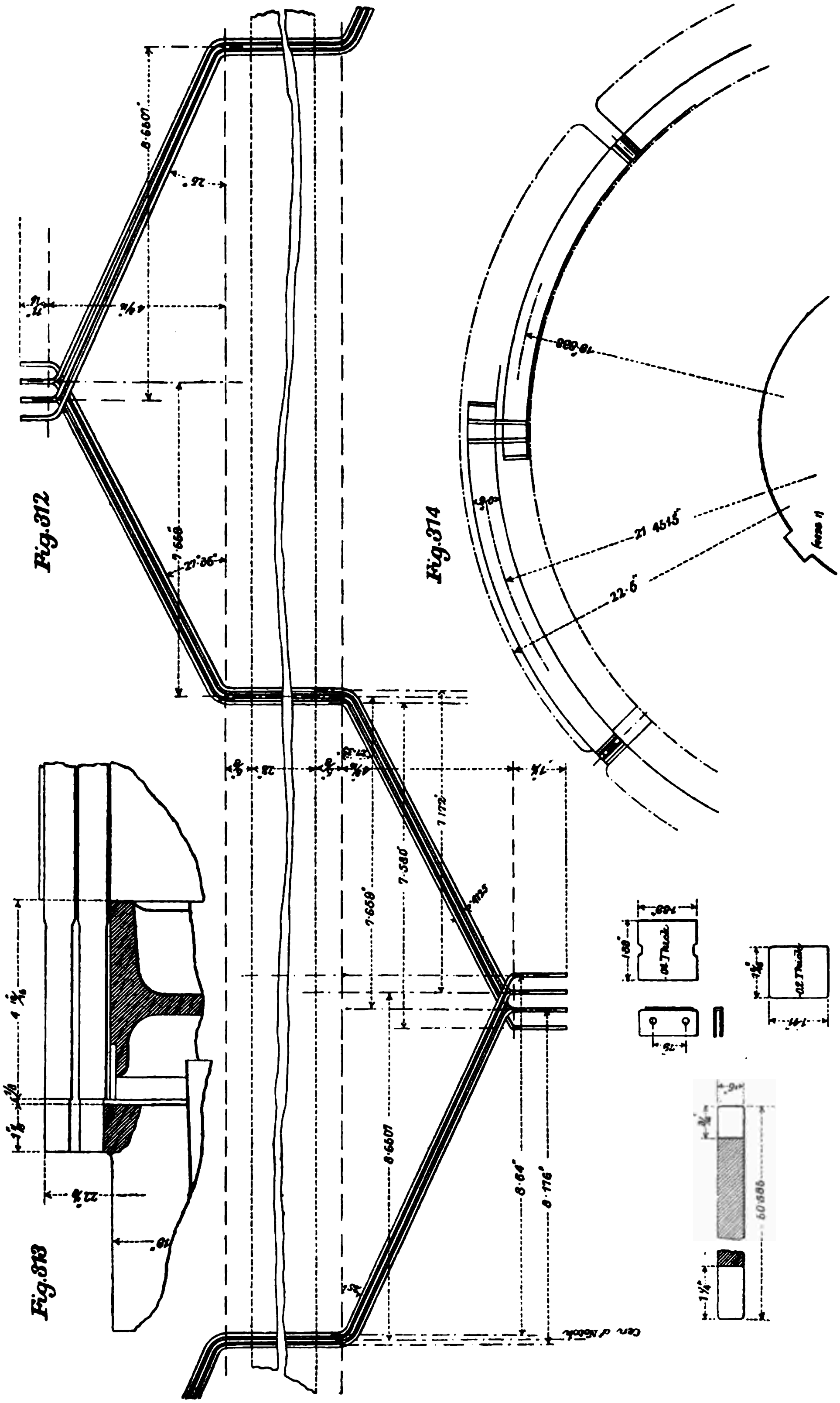
The winding on the small spools consists of fifteen turns, whose section is made up of two strips of 0.050 in. by 0.875 in., in multiple with



FIGS. 297 TO 306. DETAILS OF DIRECT-CONNECTED RAILWAY MOTOR



FIGS. 307 TO 311. DETAILS OF DIRECT-CONNECTED RAILWAY MOTOR



FIGS. 312 TO 314. ARMATURE CONSTRUCTION OF DIRECT-CONNECTED RAILWAY MOTOR

two of 0.060 in. by 0.875 in. Insulation between turns consists of a thickness of 0.010 in. of asbestos.

Cross-section of field conductor on small spools	...	... 0.193 square inch

The winding on the large spools consists of seventy-six turns, whose section is made up of a strip of 0.050 in. by $2\frac{1}{8}$ in., in multiple with one of 0.060 in. by $2\frac{1}{8}$ in.

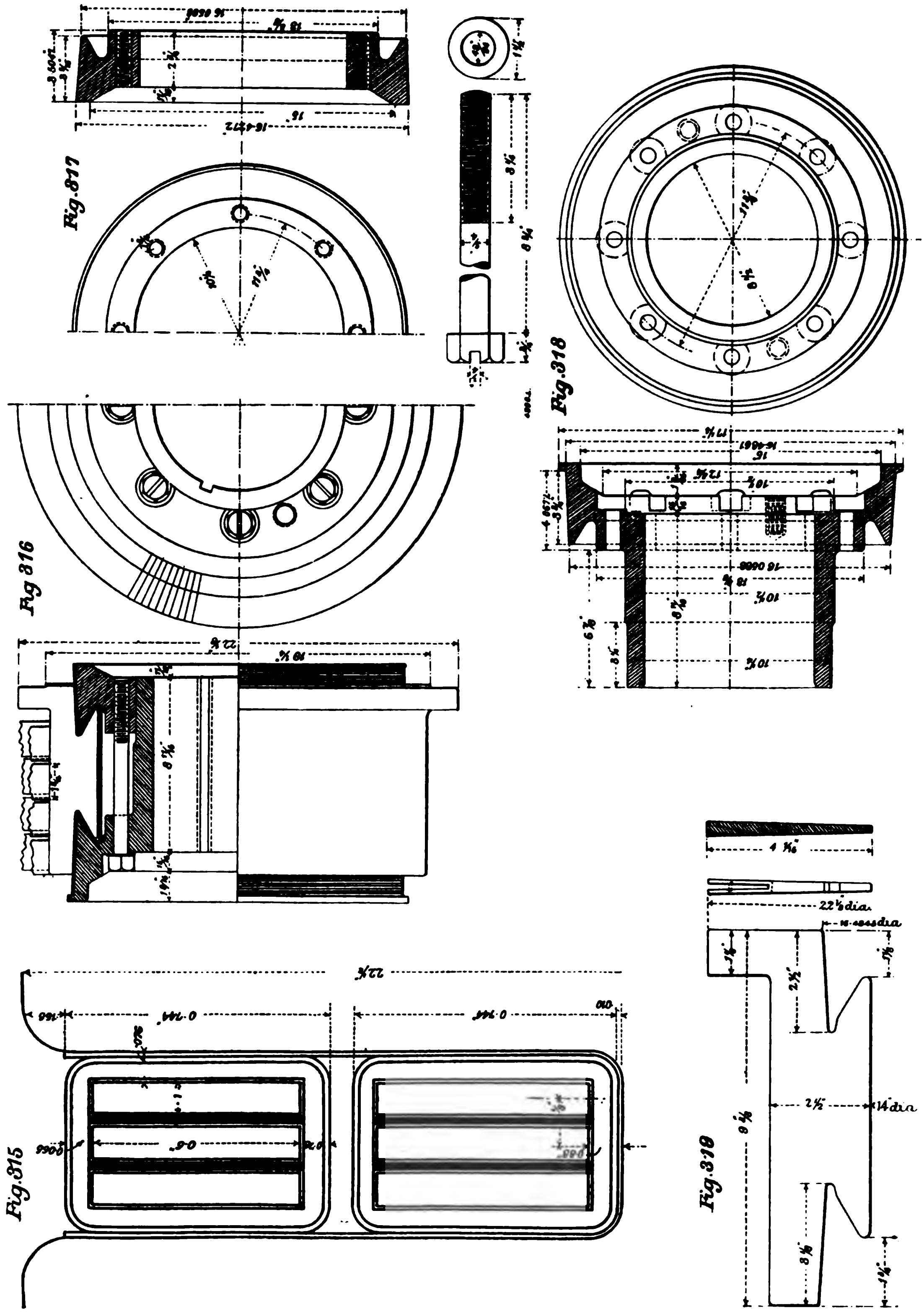
Cross-section of field conductor on large spools	...	... 0.234 square inch
Total turns on all four spools—all are in series	...	... 182
Resistance of two small spools at 70 deg. Cent.	...	... 0.012 ohm
„ „ large „ „	...	... 0.047 „
Total spool resistance at 70 deg. Cent.	...	... 0.059 „
Volts of drop in field	...	... 11 volts
Resistance of brush contacts (positive + negative)	...	... 0.012 ohm.
Volts of drop in brush contacts	...	... 2 volts
„ „ armature, field and brushes...	...	... 29 „
Counter-electromotive force of motor ...	...	... 471 „
Amperes per square inch in armature winding	...	... 2100
„ „ „ winding of small spools	...	... 1000
„ „ „ „ large „	...	... 820

Commutation:

Average voltage between commutator segments	...	... 10.7
Armature turns per pole	...	... 46
Amperes per turn	...	... 91
Armature ampere turns per pole	...	... 4200
Frequency of commutation, cycles per second	...	... 138
Number of coils simultaneously short-circuited per brush		... 3
Turns per coil		... 1
Number of conductors per group simultaneously undergoing commutation		... 6
Flux per ampere turn per inch of length of armature laminations		... 20
Flux linked with six turns with one ampere in those turns		... 3360
Inductance of one turn		... 0.0000336 henrys
The armature having a two-circuit winding with four poles and only two sets of brushes, there are two such turns in series, being commutated under the brush, and their inductance is		... 0.000067 henrys
Reactance of short-circuited turns	...	... 0.058 ohm
Amperes in „ „	...	... 91
Reactance voltage of short-circuited turns ...	...	... 5.3 volts

Magnetomotive Force Estimations

Megalines entering armature, per pole-piece ...	...	... 20.6
Coefficient of magnetic leakage taken at ...	...	... 1.15
Megalines in magnet frame, per pole-piece ...	...	... 23.8



FIGS. 315 TO 319. DETAILS OF DIRECT-CONNECTED RAILWAY MOTOR

Armature :

Section	240 square inches
Density	86 kilolines
Length, magnetic	6 in.
Ampere turns per inch of length	40
„ for armature core	240

FIG. 320

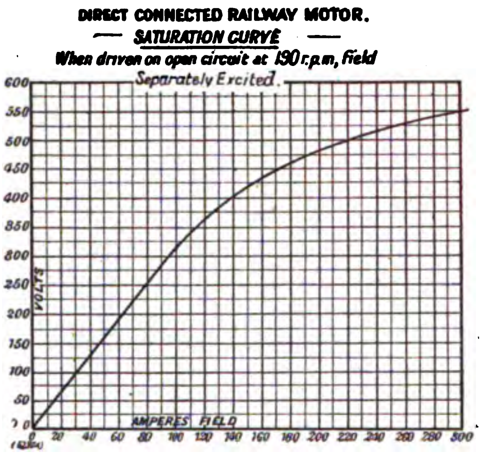


FIG. 322

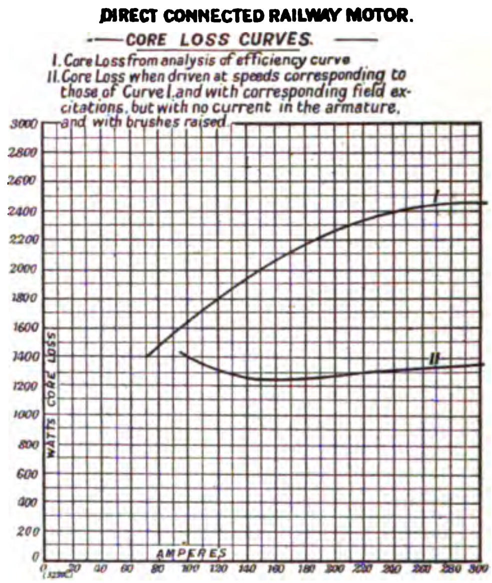


FIG. 321

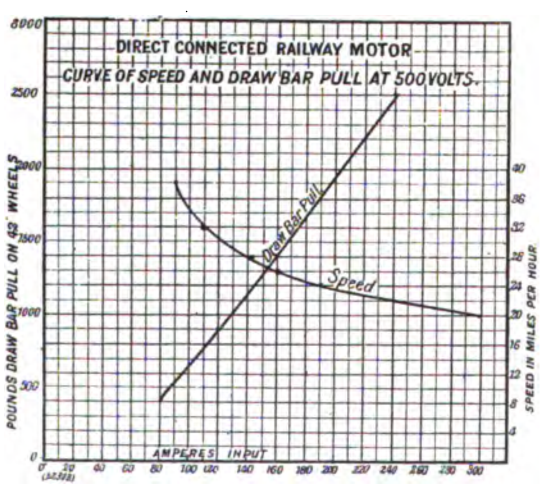
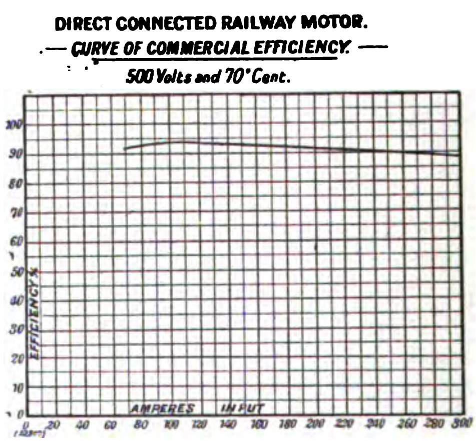


FIG. 323



FIGS. 320 TO 323. CHARACTERISTIC CURVES OF DIRECT-CONNECTED RAILWAY MOTOR

Teeth :

Transmitting flux from one pole-piece	13
Section at roots	152 square inches
Length	1.73 in.

Apparent density at tooth root	137 kilolines
Corrected ,, ,, ...	127 ,,
Ampere turns per inch of length	1000
,, for teeth	1730

Gap:

Section at pole-face	370 square inches
Length gap, average of top and bottom	0.28 in.
Density at pole-face	56 kilolines
Ampere turns for gap	5000

Cast-Steel Portion of Circuit:

Average cross-section	240 square inches
Length, magnetic	17 in.
Average density...	102 kilolines
Ampere turns per inch of length	105
,, for cast-steel frame (per pole-piece)	1780

In the following is given the estimated subdivision of the magneto-motive force observed among the different portions of the magnetic circuit:

	Ampere Turns.
Armature core	240
,, teeth	1730
Gap	5000
Cast-steel frame	1780
Total ampere turns per field spool	8750

The field excitation is furnished by two small spools on the top and bottom poles, and two large spools on the other two poles. There being fifteen turns per small spool, and seventy-six per large spool, the average excitation per spool at full rated load is $\frac{15 + 76}{2} \times 192 = 8750$ ampere turns.

Thermal Constants.

Armature:

Resistance between brushes at 70 deg. Cent....	0.084 ohm
Amperes input at rated capacity	192 amperes
Armature C^2R loss at 70 deg. Cent.	0.3100 watts
Total weight of armature laminations, including teeth	1900 lb.
Watts per pound in armature laminations	1.15 watts
Total core loss (apparently core-loss)	2200 ,,
,, of armature losses	5300 ,,
Peripheral radiating surface of armature	3250 square inches
Watts per square inch peripheral radiating surface	1.63 watts

Field Spools:

Total resistance of four field spool at 70 deg. Cent.	0.059 ohm
Spool C^2R loss at 70 deg. Cent.	2200 watts

Commutator:

Area of bearing surface of all positive brushes	4.8 square inches
Amperes per square inch of brush-bearing surface	40 amperes
Ohms per square inch of bearing surface for carbon brushes ...	0.03 ohm
Brush resistance, positive + negative	0.0125 „
Volts drop at brush contacts	2.4 volts
C^2R at brush contacts	460 watts
Brush pressure, pounds per square inch	2 lb.
Total brush pressure	19.2 „
Coefficient of friction	.3
Peripheral speed commutator, feet per minute	915
Brush friction	120 watts
Allowance for stray power lost in commutator	150 „
Total commutator loss	730 „
Radiating surface	510 square inches
Watts per square inch of radiating surface	1.43 watts

Efficiency Estimations

	Watts.
Output at rated capacity	87,500
Core loss	2,200
Commutator and brush loss	730
Armature C^2R loss at 70 deg. Cent.	3,100
Field spool C^2R loss at 70 deg. Cent.	2,200
Total input	95,730

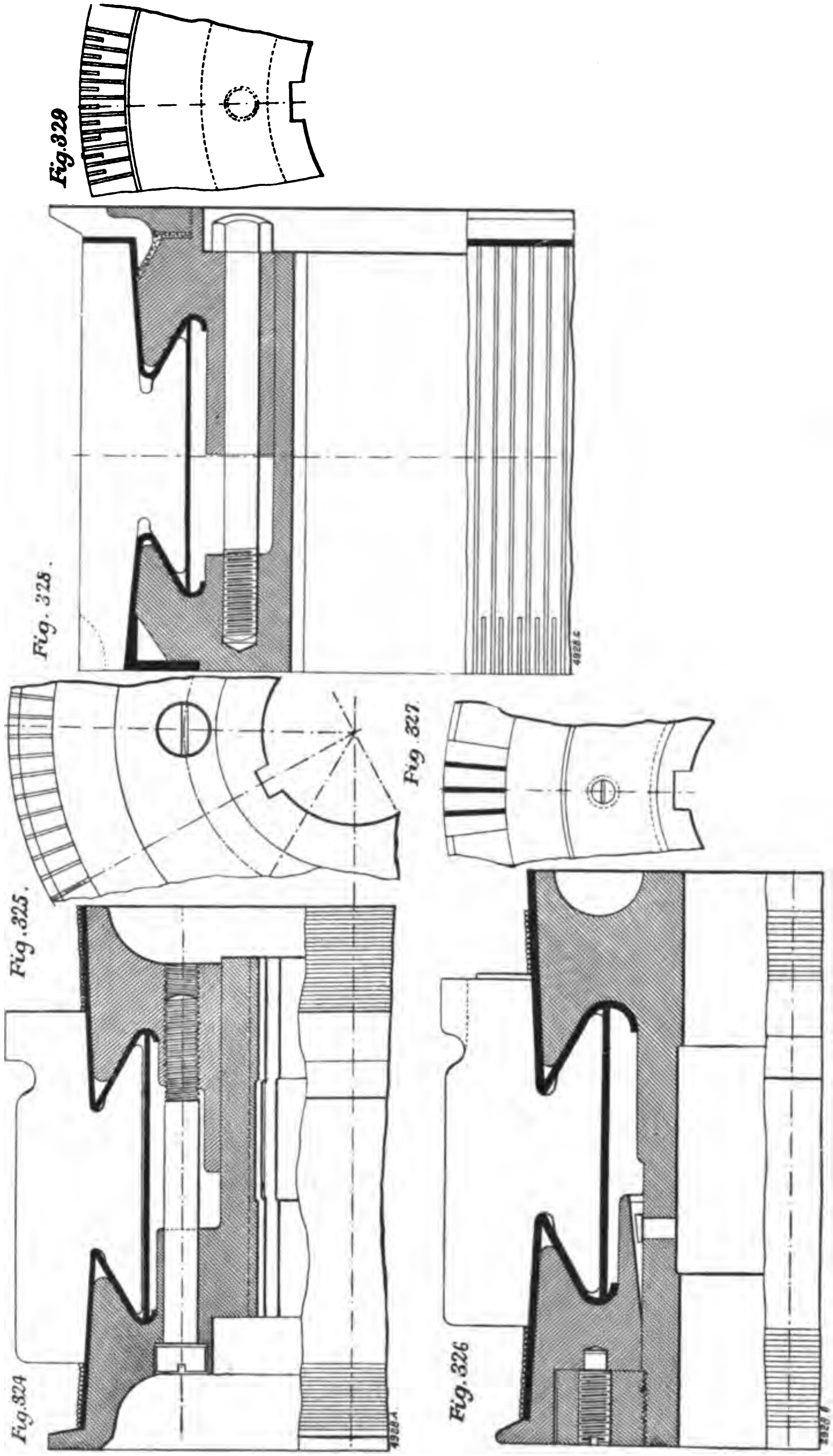
Commercial efficiency at rated capacity and 70 deg. Cent. = 91.3 per cent.

Weights

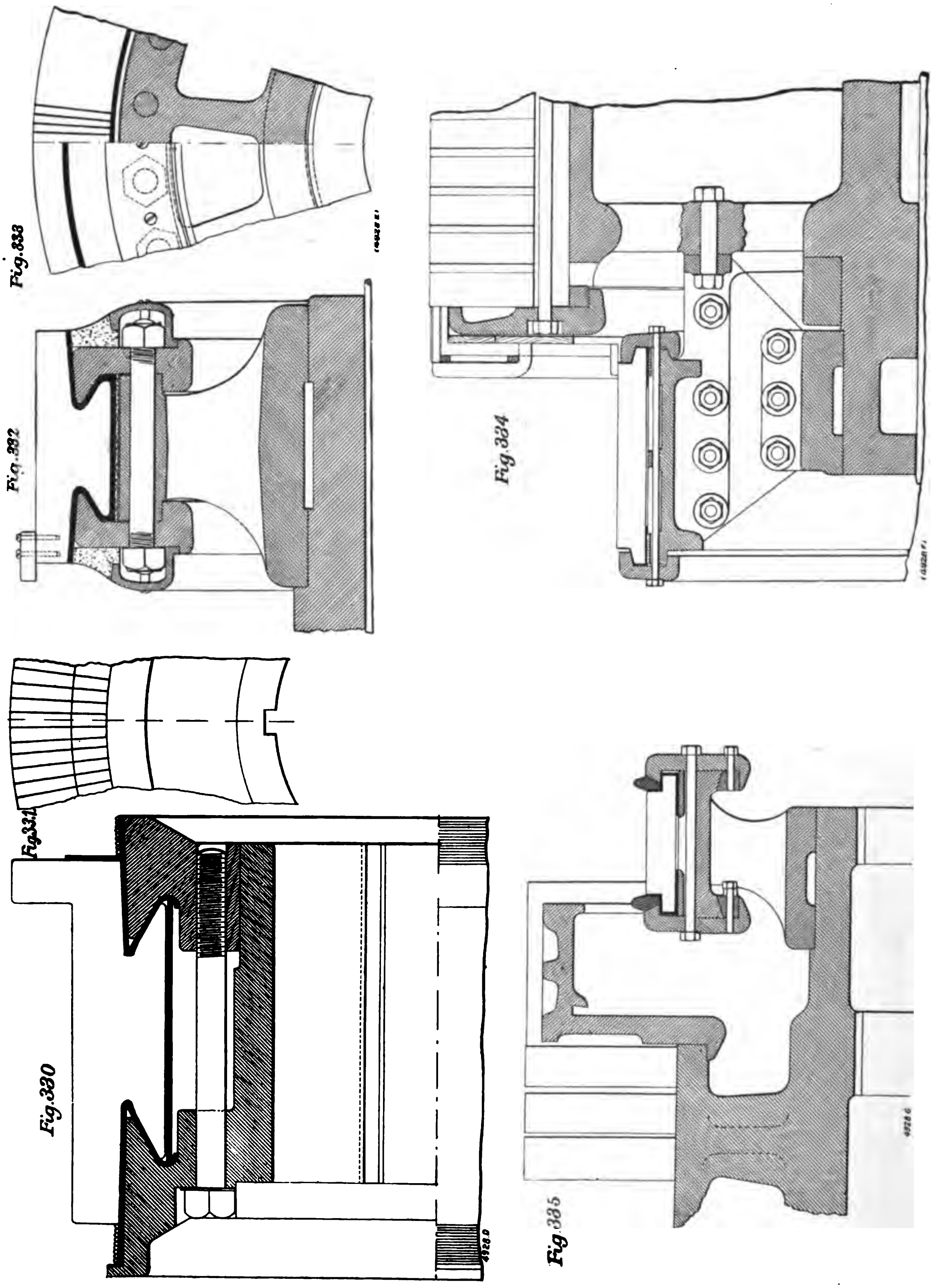
	Lb.
Weight of armature laminations	1,900
Total weight of armature copper	270
„ „ with commutator	3,000
Total weight of spool copper	1,300
„ frame with field coils	9,000
Total weight of motor	12,000

Insulation resistance, measured on 500 volts circuit, was, for the average of several motors, 2 megohms from frame to windings of armature and field, at 20 deg. Cent., and 30,000 ohms at 70 deg. Cent.

The results of experimental tests of efficiency, saturation, speed, torque, and core loss, are given in Figs. 320 to 323, page 290.



FIGS. 324 TO 329. CONSTRUCTION OF COMMUTATORS



FIGS. 330 TO 335. CONSTRUCTION OF COMMUTATORS

Fig. 336.

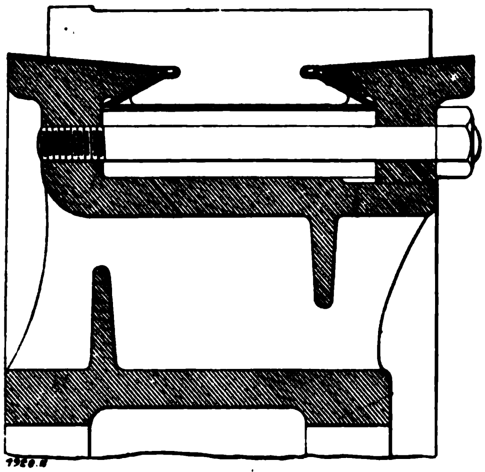


Fig. 337.

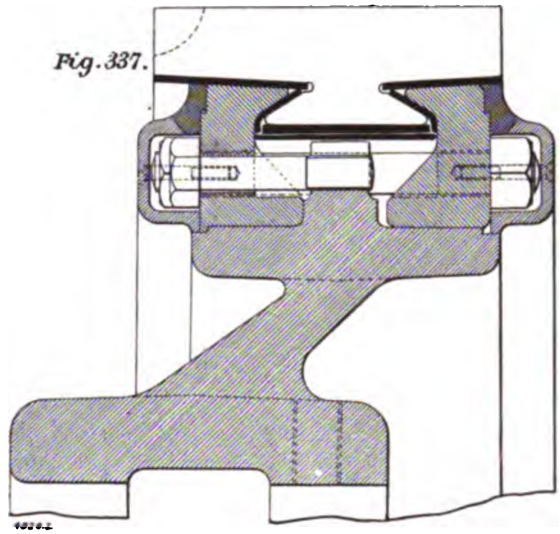


Fig. 338

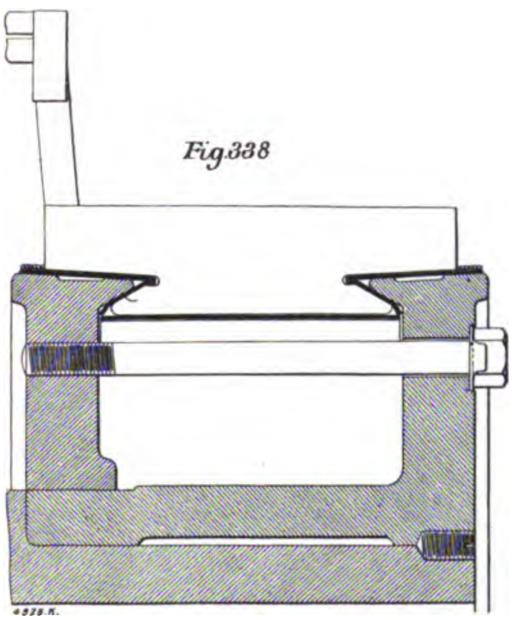


Fig. 339

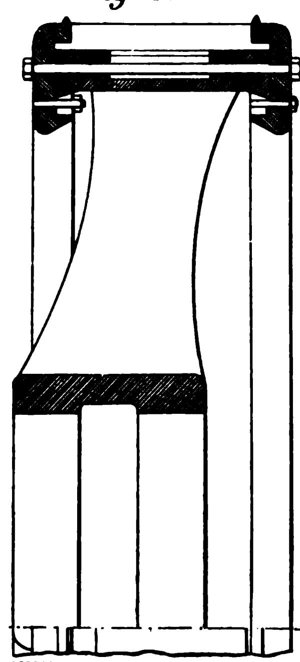
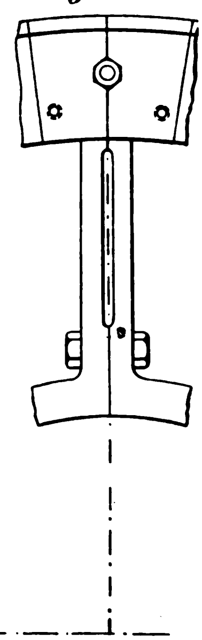


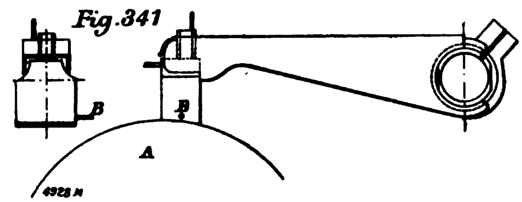
Fig. 340.



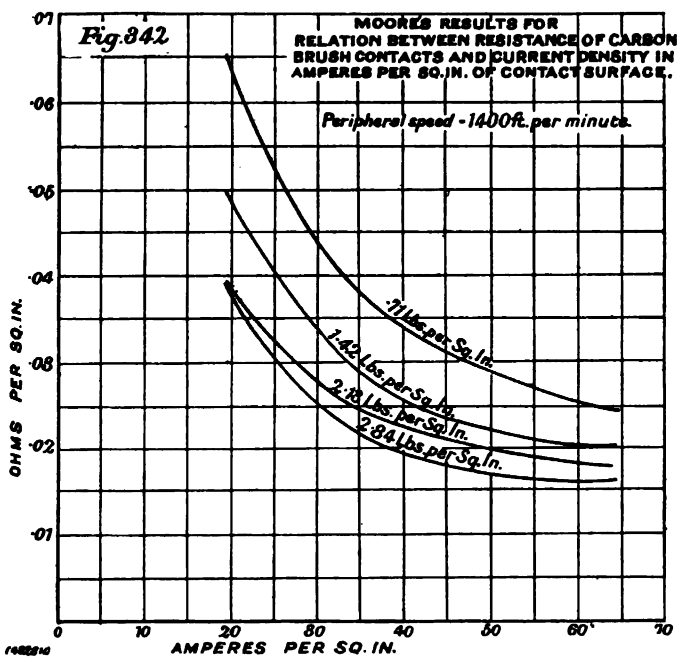
FIGS. 336 TO 340. CONSTRUCTION OF COMMUTATORS

Commutators and Brush Gear

A number of illustrations of various types of commutators are given in Figs. 324 to 340, on pages 293 to 295. Figs. 324 to 331 illustrate designs widely employed in traction motors, that of Figs. 330 and 331 being used on a 100 horse-power direct-connected motor, the three former in smaller, geared motors.

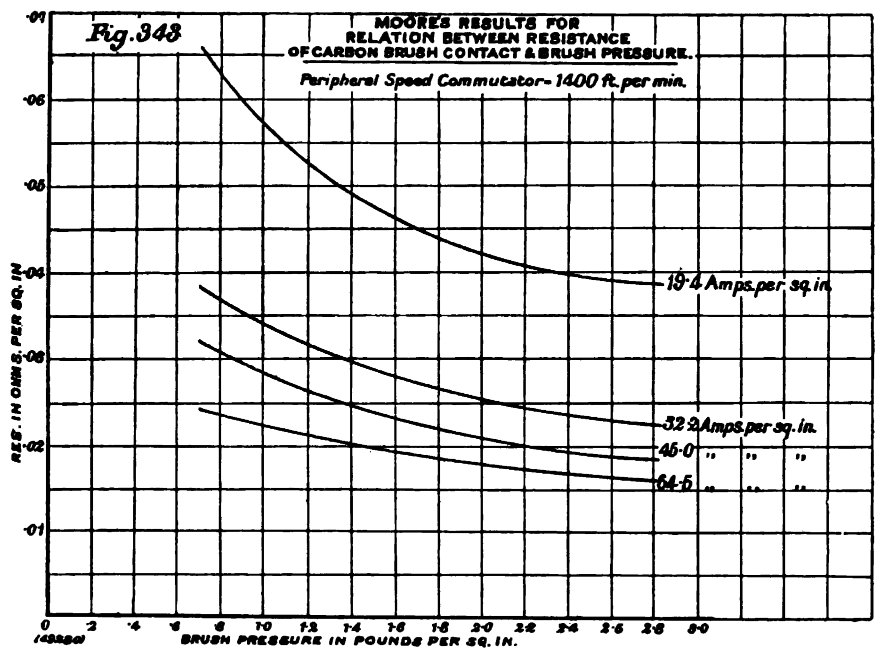


Arrangement of Apparatus for Moore's Investigation of the Relations between Resistance of Carbon Brush Contacts and Current Density in Amperes per Square Inch of Contact Surface. Resistance measured from A to B.



Figs. 332 to 334 give some early designs of Mr. Parshall's, which have been much used with general success in many later machines, especially for traction. Other useful modifications and alternative designs are shown in Figs. 335 to 340, the last one being employed in a 1600-kilowatt generator.

Commutator segments should preferably be drawn, although good results have also been attained with drop-forged segments; cast segments have been generally unsatisfactory. It is not on the score of its superior conductivity that wrought-copper segments are necessary, since the loss due to the resistance itself is negligible, but it is of primary importance that the material shall possess the greatest possible uniformity throughout, and freedom from any sort of flaw or inequality. Any such that may develop during the life of the segments will render the commutator unequal to further thoroughly satisfactory service until turned down or

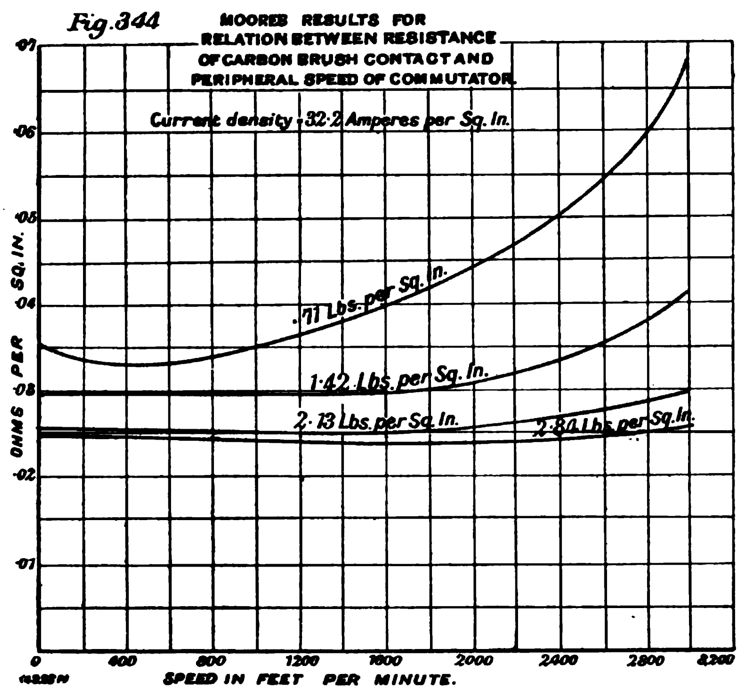


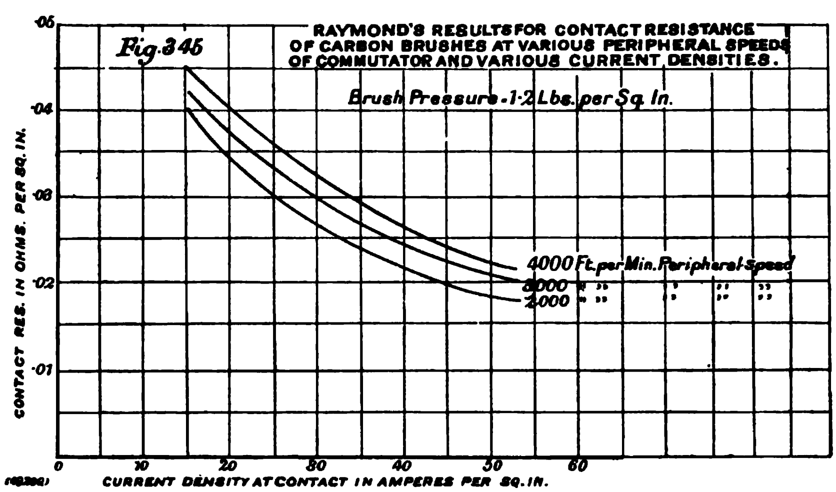
otherwise remedied, as the effect of uneven wear, once started, is cumulative. For similar reasons great care must be exercised in the selection of the mica for the insulation between segments; it should preferably be just soft enough to wear at the same rate as the copper, but should in no event wear away more slowly, as under such conditions the commutator will not continue to present a suitably smooth surface to the brush.

The writers have found the method of predetermining the commutator losses and heating, set forth briefly on page 112, to give very good results, and to amply cover practical determinations. But an intelligent handling of the subject of the relations existing between commutator speeds, brush pressure, and contact resistance, is facilitated

by a study of the results of tests that have been made, showing the dependence of these values upon various conditions.

The most complete and careful tests on carbon brushes at present





available, appear to be those conducted by Mr. A. H. Moore, in 1898, and the results are graphically represented in Figs. 341 to 344. In Fig. 341 is given a sketch showing the disposition and nature of the parts. A rotating cylinder, A, of 6.8 in. diameter, of cast copper, took the

place of a commutator, and this introduced an element of doubt as to whether a segmental structure of hard-drawn copper segments and mica would have given the same results. But inasmuch as the constants derived from these tests agree with those which have been found to lead to correct predictions of the performance of new commutators, it may be safely concluded that this point of dissimilarity was of no special consequence. In all other respects the tests seem especially good. The set of test also includes values for the resistances of the brush holders, but with good designs of brush holders the resistance should be negligible;

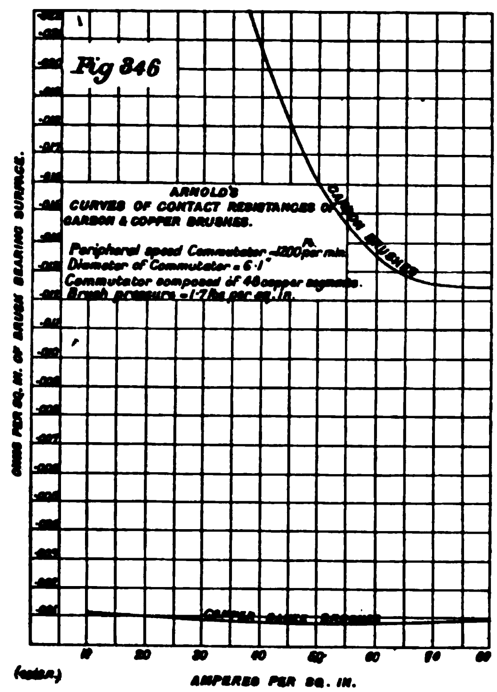
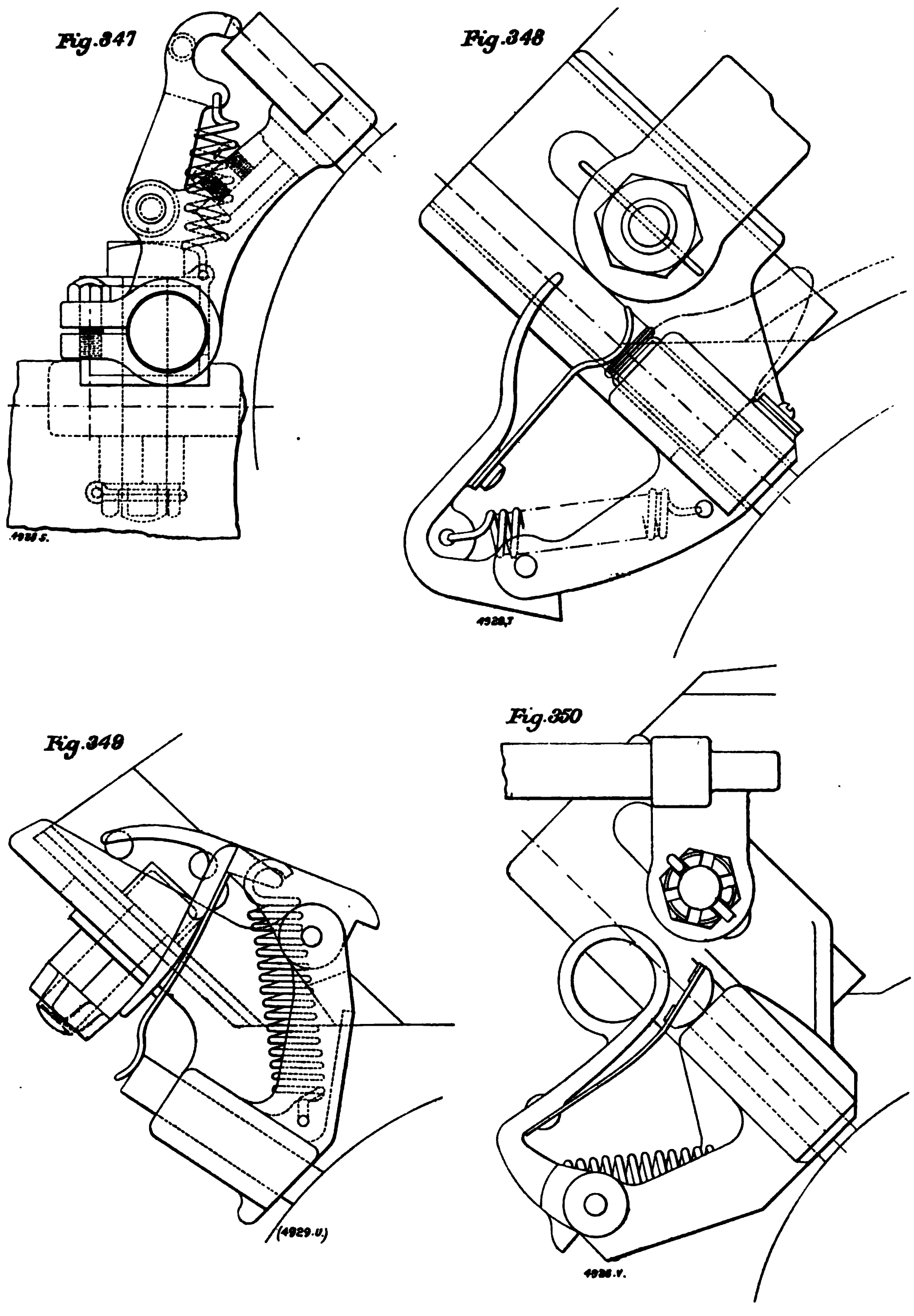


Fig 346

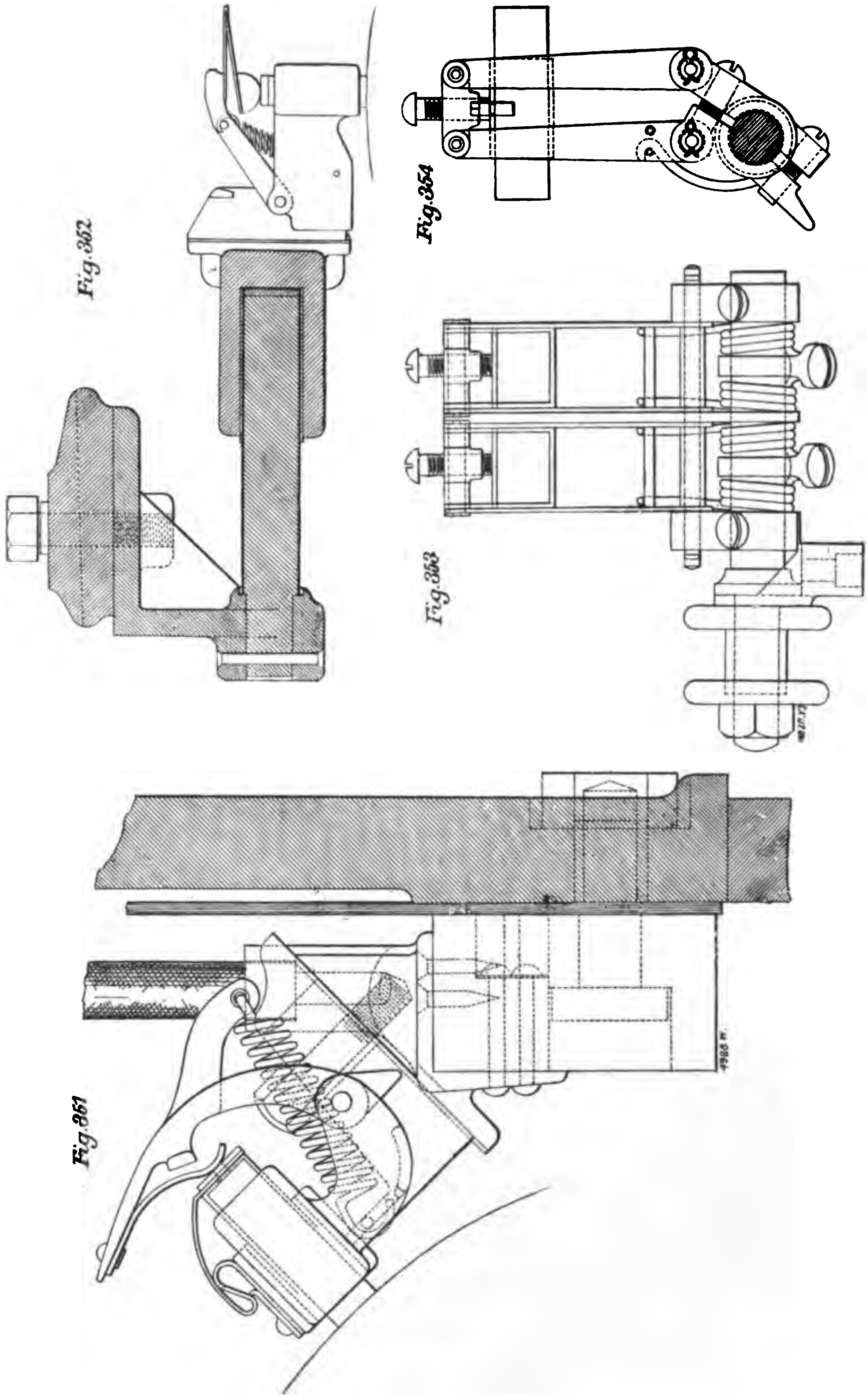
hence it has been deemed advisable not to divert attention from the important results relating to contact resistance, by the addition of these less useful observed values.

Mr. E. B. Raymond has, in America, conducted tests on this same subject. Some of the results for carbon brushes are shown in the curves of Fig. 345; and it will be observed that, for all practical purposes, his results, like Mr. Moore's, lead to the general working constants given on page 112.

Dr. E. Arnold, in the *Electrotechnische Zeitschrift*, of January 5th, 1899, page 5, described investigations on both copper and carbon brushes,



FIGS. 347 TO 350. BRUSH-HOLDERS



FIGS. 351 TO 354. BRUSH-HOLDERS

from which have been derived the curves set forth in Fig. 346, page 299, showing the relative values for the contact resistances in the two cases. Dr. Arnold also points out that while the coefficient of friction for carbon brushes on copper commutators is in the neighbourhood of 0.3, he has found 0.2 to be a more suitable value for copper-gauze brushes. But in the absence of thorough tests in support of this, the writers would be inclined to continue using a coefficient of 0.3 for both carbon and copper brushes.[1]

Of course, all values relating to this whole matter of commutator losses must necessarily be, in practice, but little better than very roughly approximate, as they are so dependent upon the material, quality, and adjustment of the brushes, and the condition of their surfaces, as also upon the construction, condition, and material of the commutator and brush holders, and—fully as important as anything else—upon the electromagnetic properties of the design of the dynamo.

Various designs of brush holders for generators and railway motors are given in Figs. 347 to 365, pages 300 to 304, the first six (Figs. 347 to 352) being for use with radial carbon brushes on traction motors, where the direction of running is frequently reversed. In Figs. 353 and 354 is shown a brush holder which has been used on a 3 horse-power launch motor, for reversible running, with carbon brushes. Figs. 355 to 358 illustrate useful types for generators with carbon brushes, and in Fig. 359 is shown a holder designed for a copper-gauze brush.

The Bayliss reaction brush holder, shown in Figs. 360 and 361, is one of the latest and most successful developments in brush-holder design. Another design, where the holder is constructed largely of stamped parts, is given in Figs. 362 and 363. The holder shown in Figs. 364 and 365 is essentially a modification of the design represented in Fig. 357.

Of carbon brushes a wide range of grades have been used, varying from the soft, amorphous, graphite brushes up to hard, rather crystalline,

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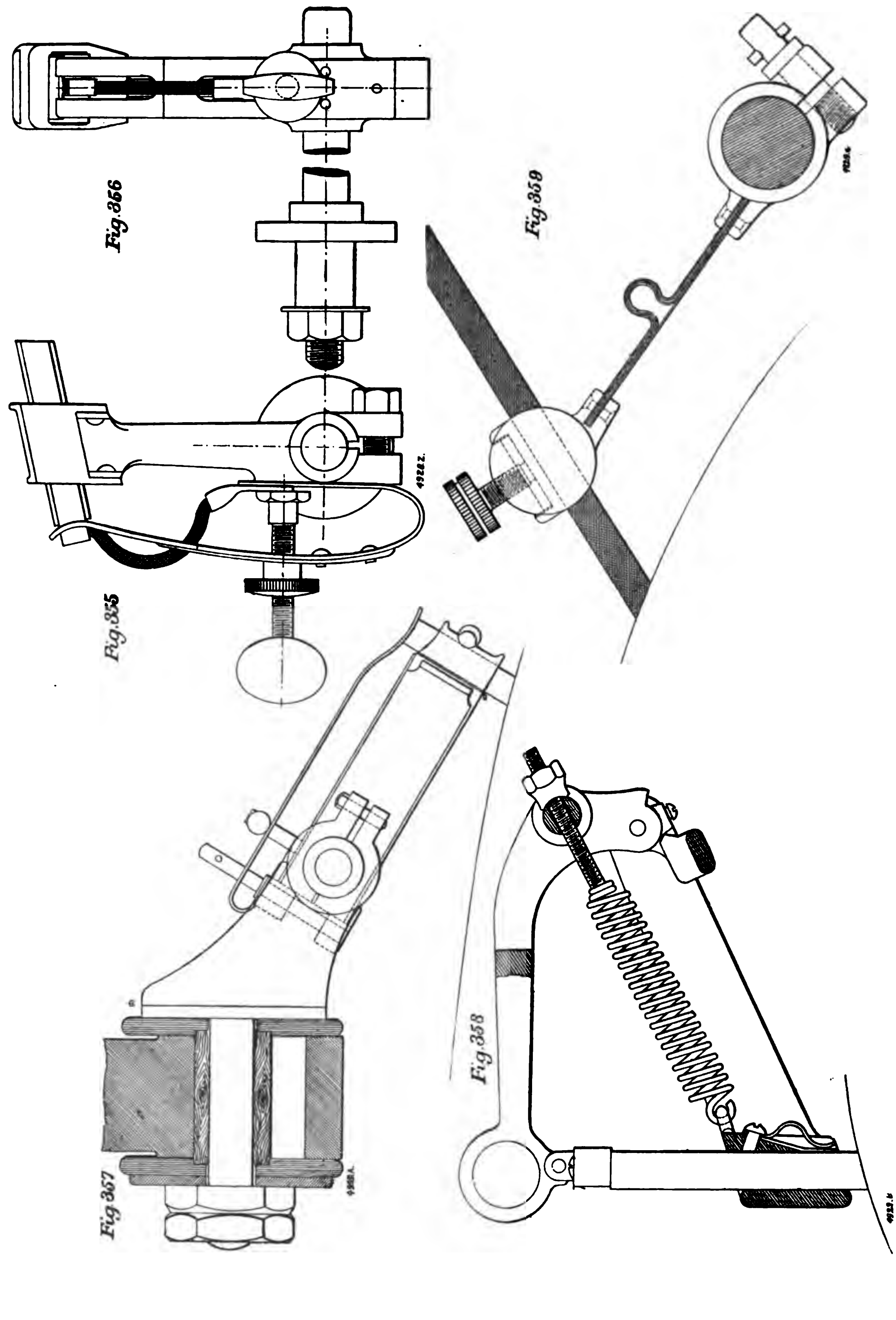
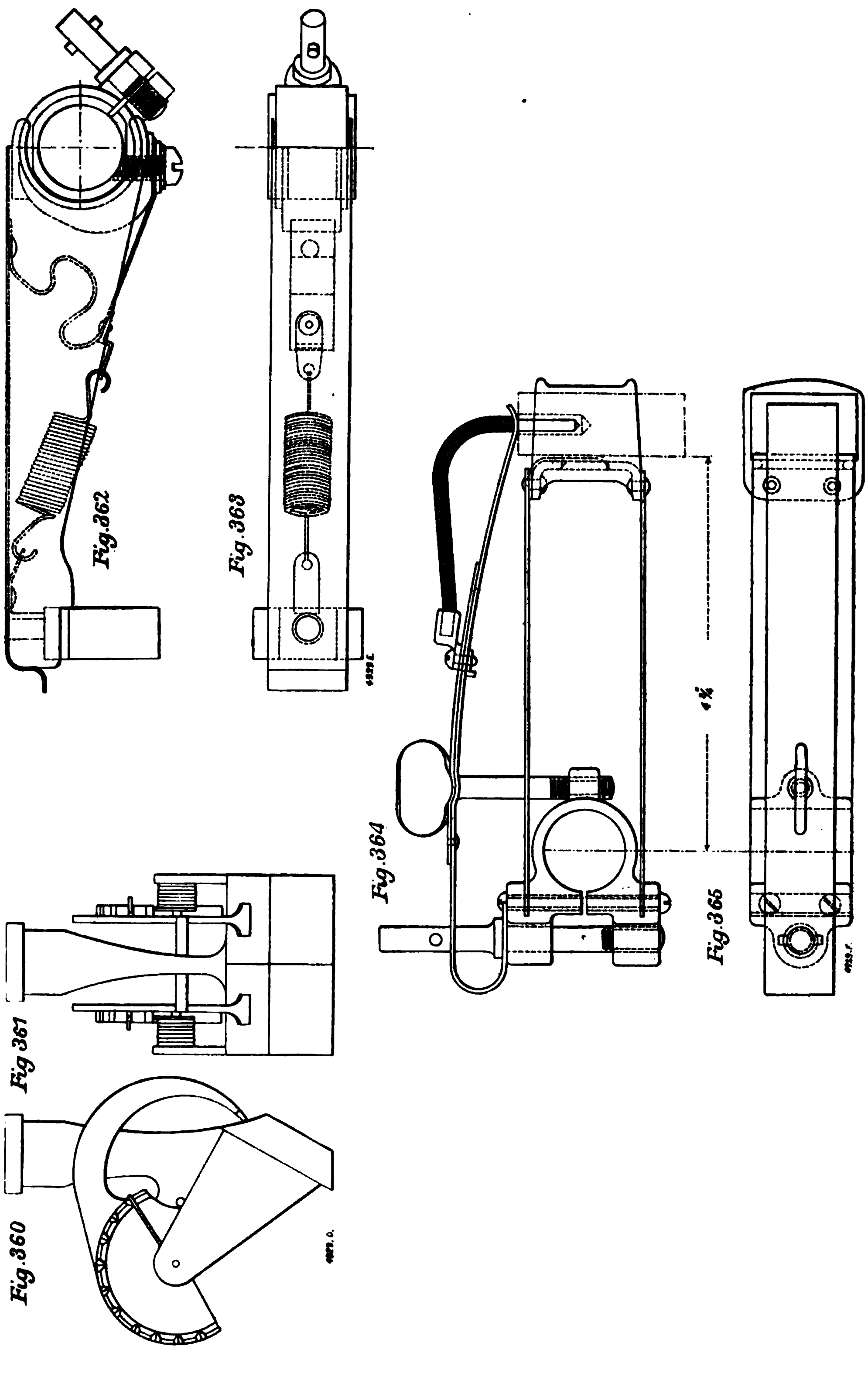
[1] Tibbals, Löwenberg and Burnshave (*Electrical World and Engineer*, September 16, 1899), and Hellmund (*Elektrotechn. Zeitschr.*, September 11, 1902) have made investigations regarding brush friction losses. Especially exhaustive experiments have been made by Dettmar (*Elektrotechn. Zeitschr.*, May 31, 1900), who studied the dependency of the contact resistance upon speed, pressure and current density, for slip-rings as well as for commutators. The tests of Bourguignon (*Société Electr. Bull.*, January, 1903), though very instructive, are of less practical usefulness, due to the use of a higher pressure per square centimetre than is usual in modern practice.



Figs. 335 to 359. Brush-Holders



Figs. 360 to 365. Brush-Holders

carbon brushes. The latter have the lower specific resistance,[1] a lower contact resistance, and a lower coefficient of friction on copper commutators, and are for most cases much to be preferred. Tests made by Mr. Raymond show the extent of these differences between graphite and carbon brushes of two representative grades.

TABLE LVI.—RAYMOND'S TESTS ON GRAPHITE AND CARBON BRUSHES

Amperes per Square Inch of Brush-bearing Surface.	Ohms per Square Inch of Brush-bearing Surface. Graphite.	Carbon.
10	0.075	0.048
20	0.045	0.035
30	0.033	0.026
40	0.027	0.022
50	0.022	0.019
60	0.019	0.017
70	0.017	—
80	0.015	—

The above results were obtained at peripheral speeds in the neighbourhood of 2000 ft. per minute, and with brush pressures of about 1.3 lb. per square inch.

While the coefficient of friction for carbon brushes is about 0.3, Mr. Raymond obtained the value of 0.47 for these graphite brushes.

The specific resistance of a good grade of carbon brush is 2500 microhms per cubic inch, *i.e.*, about 4000 times the resistance of copper.

Another objection to graphite brushes, at any rate on higher potential commutators, say 500 volts, is that they are liable to have their contact surface gradually pitted out to a greater extent than occurs with the hard-grained, coarser carbon brushes. Nevertheless, the matter of obtaining the best commutating conditions for each particular case still remains partly experimental, and graphite brushes have, in certain instances, been found helpful, although the commutator surface requires more constant attention to be kept clean and bright; indeed, with soft graphite brushes it is almost impossible to obtain such a hard, glazed, commutator surface, as with coarser, harder carbon brushes.

There are very many more varieties of brushes, made of all sorts of

[1] Some types of graphite brushes have a lower specific resistance than some types of carbon brushes. A great deal depends upon the composition and upon the methods of manufacture. By varying these, a wide range of specific resistances may be obtained, both for carbon and for graphite brushes.

materials, and giving many intermediate grades of resistances, lying between the limits of carbon and copper. It is not worth while to attempt to classify and describe these varieties of brushes ; their relative merits are dependent partly upon the choice of materials, but still more upon the methods of constructing the brush from these materials. Scarcely any one type of brush and grade of resistance is suitable for any considerable range of variety of dynamo-electric machine.

PART III

ROTARY CONVERTERS

ROTARY CONVERTERS

A ROTARY converter is, structurally, in many respects similar to a continuous-current generator, the chief outward difference consisting in the addition of a number of collector rings, and in the commutator being very much larger, in comparison with the dimensions of the rest of the machine, than in an ordinary continuous-current dynamo. Under the usual conditions of running, the armature is driven, as in a plain synchronous motor, by alternating current, supplied to the collector rings from an external source. Superposed upon this motor current in the armature winding is the generator current, which is delivered from the commutator to the external circuit as continuous current. Occasionally rotary converters are used for just the opposite purpose, namely, to convert continuous into alternating current. With this latter arrangement, however, some sort of centrifugal cut-off governor should always be used, as the reactions on the field strength occasioned by sudden changes in the alternating-current load may so weaken the field as to cause dangerous increase of speed. But in by far the greater number of cases the apparatus is employed for transforming from alternating to continuous current.

The most interesting property of a rotary converter is the overlapping of the motor and generator currents in the armature conductors; in virtue of which, not only may the conductors be of very small cross-section for a given output, from the thermal standpoint, but, the armature reactions also being neutralised, large numbers of conductors may be employed on the armature, which permits of a very small flux per pole-piece, and a correspondingly small cross-section of magnetic circuit. The commutator, however, must be as large as for a continuous-current generator of the same output; hence a consistently designed rotary converter should be characterised by a relatively large commutator, and small electro-magnetic system. This is best achieved by an armature of fairly large diameter and small axial length; this, furthermore, gives

room for the many, though small, armature conductors, and for the many poles required for obtaining reasonable speeds at economical periodicities. The mechanical limit imposed by centrifugal force becomes an important factor in the design of the armature and commutator of a rotary converter, as compared with continuous-current generators.

In some installations a good deal has been heard of "surging" troubles in operating rotary converters. These were largely due to insufficiently uniform angular velocity of the engines driving the Central Station generators, whose power was ultimately used to operate the rotary converters. This lack of uniformity in angular velocity had the effect of causing cumulative oscillations in the rotary converters, in their efforts to keep perfectly in synchronism with the direct-driven generators throughout a revolution. This caused especial difficulty when it was attempted to operate several rotary converters at different sub-stations in parallel. The true solution for these difficulties is to have engines of such design as to give uniform angular velocity. In describing the proper lines on which to design rotary converters, it will be assumed that this condition, as regards the generating set, has been complied with; otherwise it is necessary to employ auxiliary devices to counteract such influences, and there results a serious loss in economy through the dissipation of energy in steadying devices.

TABLE LVII.—OUTPUT IN TERMS OF OUTPUT OF CONTINUOUS-CURRENT GENERATOR FOR EQUAL C^2R LOSS IN ARMATURE CONDUCTORS FOR UNITY POWER FACTOR, AND ON THE ASSUMPTION OF A CONVERSION EFFICIENCY OF 100 PER CENT.

Type of Rotary Converter.	Number of Collector Rings.	Uniform Distribution of Magnetic Flux over Pole-Face Spanning Entire Polar Pitch.	Uniform Distribution of Magnetic Flux over Surface of Pole-Faces Spanning 67 per Cent. of Entire Polar Pitch.
Single phase ...	2	0.85	0.88
Three " ...	3	1.34	1.38
Four " ...	4	1.64	1.67
Six " ...	6	1.96	1.98
Twelve " ...	12	2.24	2.26

The extent to which the motor and generator currents neutralise one another, and permit of small armature conductors to carry the residual

current, varies with the number of phases. Table LVII. gives the output of a rotary converter for a given C^2R loss in the armature conductors, in terms of the output of the same armature when used as a continuous-current generator, this latter being taken at 1.00.

Table LVIII. shows the extent to which the preceding values have to be modified for power factors other than unity.

TABLE LVIII.—OUTPUT IN TERMS OF OUTPUT OF CONTINUOUS-CURRENT GENERATOR FOR EQUAL C^2R LOSS IN ARMATURE CONDUCTORS FOR 100 PER CENT. EFFICIENCY, AND FOR UNIFORM GAP DISTRIBUTION OF MAGNETIC FLUX OVER A POLE-FACE SPANNING 67 PER CENT. OF THE POLAR PITCH

Type of Rotary Converter.	Number of Collector Rings.	Power Factor of		
		1.00.	0.90.	0.80.
Single phase	2	0.88	0.81	0.73
Three „	3	1.38	1.28	1.17
Four „	4	1.67	1.60	1.44
Six „	6	1.98	1.92	1.77
Twelve „	12	2.26	2.20	2.05

The writers have investigated by graphical and other methods the subject of the C^2R loss in the armature of a three-phase rotary converter, in comparison with the C^2R loss for the same load delivered from the commutator when the machine is used in the ordinary way as a mechanically-driven continuous-current dynamo. Not only are the results of considerable value, but a study of the graphical method of investigation pursued, leads to an understanding of many interesting features of the rotary converter.

As a basis for the analysis, Figs. 366 to 369, pages 312 to 315, were prepared. In Fig. 366 are given sine curves of instantaneous current values in the three sections of the armature winding (as it would be if the alternating currents alone were present), and also the corresponding curves of resultant current in the three lines leading to the collector rings. The first three curves are lettered *a*, *b*, and *c*, and a current clockwise directed about the delta is indicated as positive. The line currents are derived by Kirchhoff's law, that the sum of the currents from the common junction of several conductors must always equal zero. Outwardly-directed

currents are considered positive. These curves of resultant line current are designated in Fig. 366 as *a-b*, *b-c*, and *c-a*. Thirteen ordinates, lettered from A to M, divide one complete cycle up into 30 deg. sections. In Fig. 367 are given diagrams of line and winding currents from each of the ordinates from A to F. The remainder, *i.e.*, from G to M, would merely be a repetition of these. An examination shows that these six diagrams, so far as relates to current magnitudes, are of two kinds, of which A and B

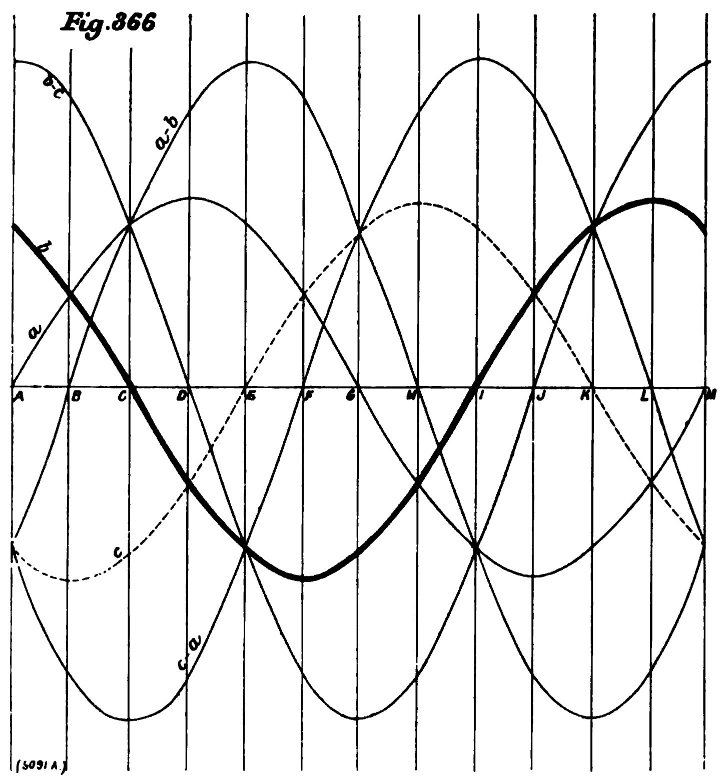


FIG. 366. CURRENT CURVES

are the types. In A, the three current values in the windings are respectively 0, 0.867 and—0.867, whilst these become in B, 0.5, 0.5 and —1.00. Hence it is sufficient for practical purposes to study the current distribution in the armature conductors corresponding to positions A and B, and to then calculate the average C^2R loss for these two positions. For this purpose, developed diagrams have been mapped out in Figs. 368 and 369, for the winding of a rotary converter, from whose commutator 100 amperes at 100 volts are to be delivered from each pair (positive and negative) of brushes. The number of poles is immaterial. The armature

has a multiple-circuit single winding, and it may be assumed that there are two conductors per slot, though this assumption is not necessary. It was thought best to take a fairly large number of conductors, and to take into account, just as it comes, the disturbing influence of the brushes, which somewhat modifies the final result. Of course, this disturbing influence would vary with the width of the brushes. Comparatively narrow brushes are shown, and this will tend to offset the circumstance

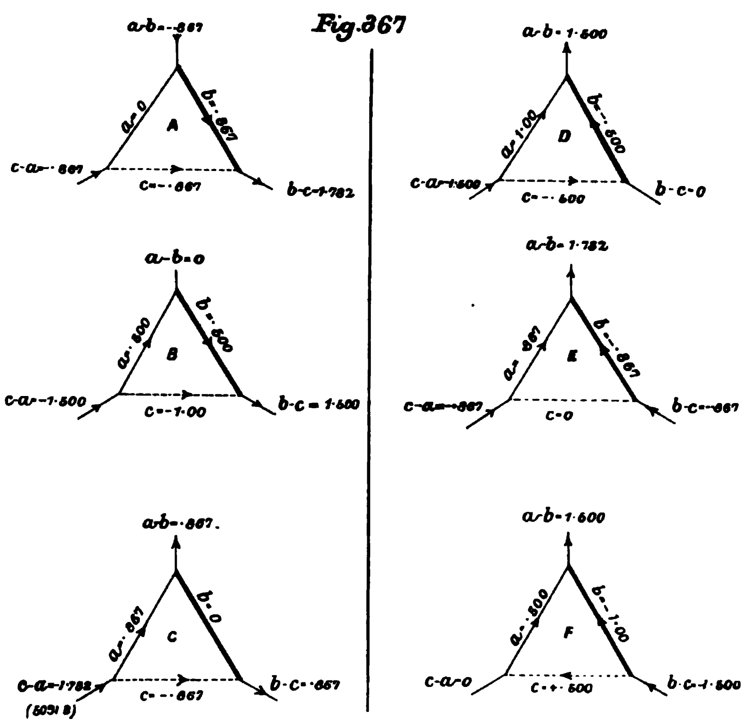
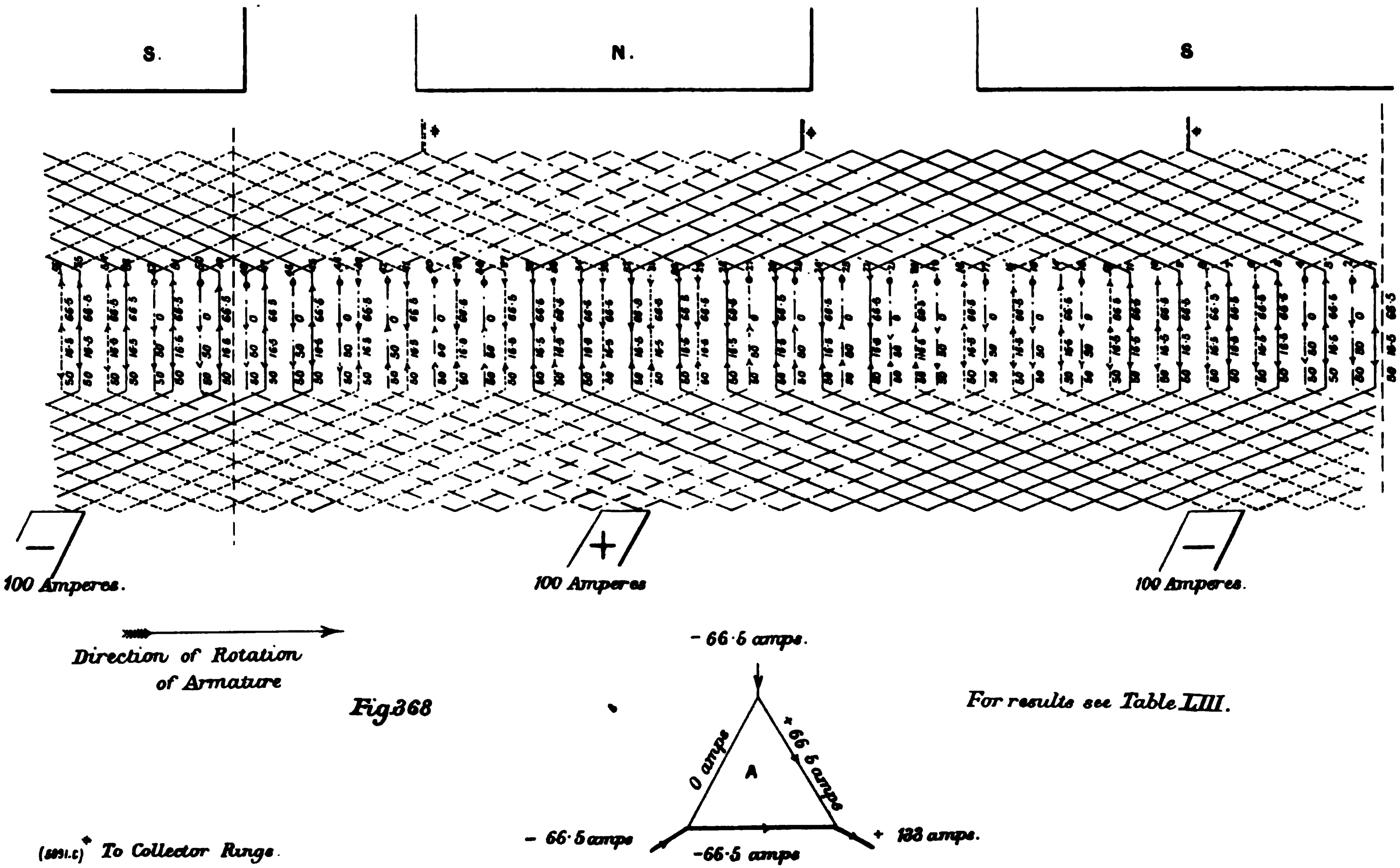


FIG. 367. DIAGRAMS OF LINE- AND WINDING-CURRENTS

that the number of conductors is considerably less than would be taken in practice for this voltage.

The assumption is made that the rotary converter is of 100 per cent. efficiency, only calling for an input equal to the output. To supply 100 amperes to the commutator brushes calls for 50 amperes per conductor, so far as the continuous-current end is concerned. This is shown in direction and magnitude by arrow-heads and figures at the lower ends of the vertical lines representing face conductors.

100 volts and 100 amperes give 10,000 watts per pair of poles. Therefore, input per phase = 3330 watts. Volts between collector rings



NOTE.—In the above and opposite diagrams (Figs. 368 and 369) the figures on the right hand of the vertical lines should in each case be referred to positions immediately under the arrow heads.

FIG. 368 DIAGRAM OF ROTARY-CONVERTER WINDING

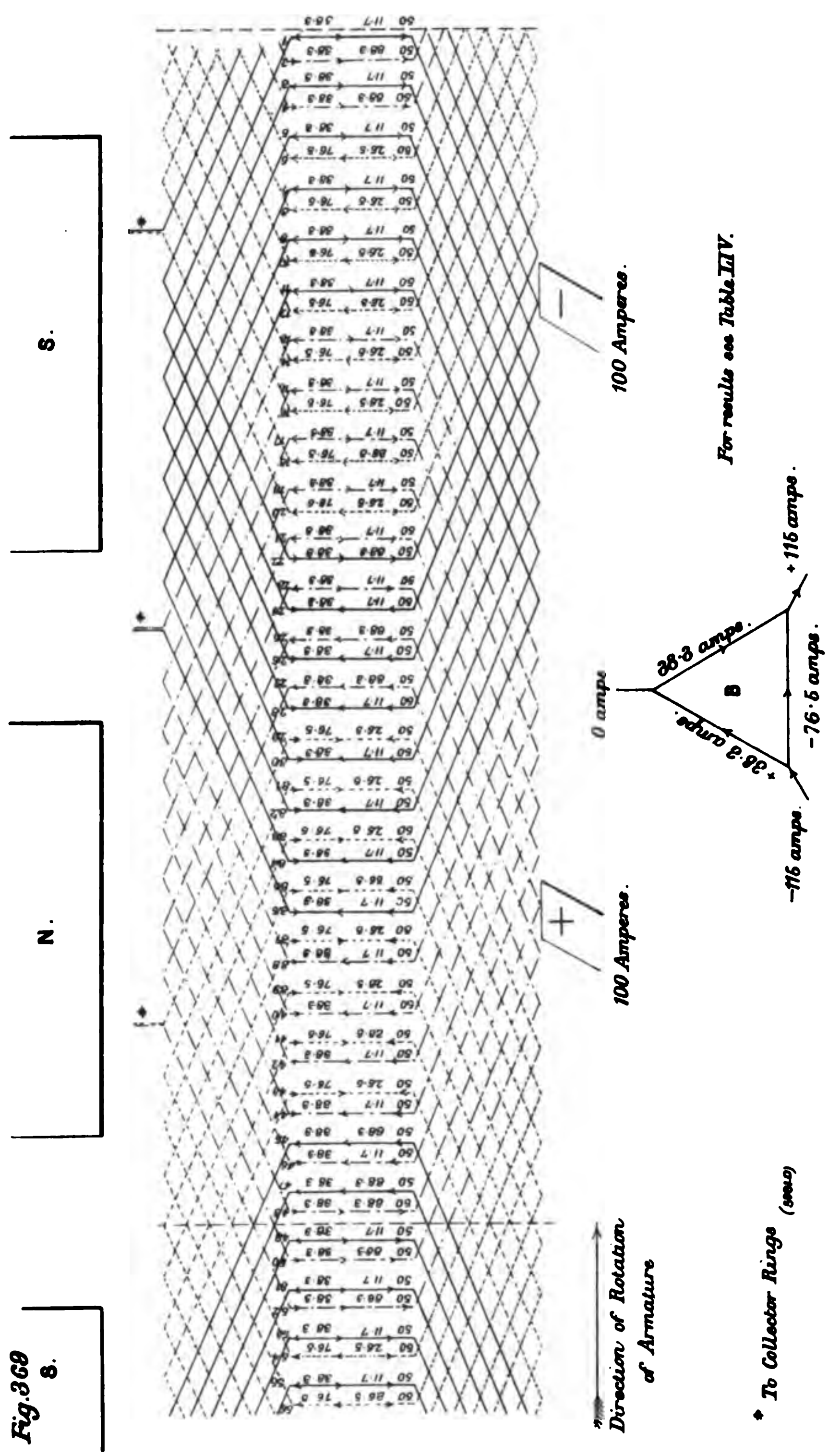


Fig. 369. Diagram of Rotary-Converter Winding

TABLE LIX. (*See page* 320.)

Number of Conductor.	Current in Phase. Continuous Current.	Current in Phase. Alternating Current.	Current in Phase. Resultant Current.	Current in Phase. $(Current)^2$.	Current 30 Deg. out of Phase. Cos. 30 Deg. = .866. Continuous Current.	Current 30 Deg. out of Phase. Alternating Current, not Considering Power Factor.	Current 30 Deg. out of Phase. Alternating Current ÷ .866	Current 30 Deg. out of Phase. Resultant Current.	Current 30 Deg. out of Phase. $(Current)^2$	Current 60 Deg. out of Phase. Cos. 60 Deg. = .500. Continuous Current.	Current 60 Deg. out of Phase. Alternating Current, not Considering Power Factor.	Current 60 Deg. out of Phase. Alternating Current ÷ .500	Current 60 Deg. out of Phase. Resultant Current.	Current 60 Deg. out of Phase. $(Current)^2$.
1	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
2	− 50	0	− 50	2,500	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
3	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
4	− 50	0	− 50	2,500	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
5	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	0	0	− 50	2,500
6	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
7	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	0	0	− 50	2,500
8	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
9	− 50	+ 66.5	+ 16.5	272	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
10	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
11	− 50	+ 66.5	+ 16.5	272	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
12	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
13	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
14	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	− 66.5	− 133	− 183	33,500
15	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
16	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	− 66.5	− 133	− 183	33,500
17	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
18	− 50	+ 66.5	+ 16.5	272	− 60	− 66.5	− 76.7	− 126.7	16,000	− 50	− 66.5	− 133	− 183	33,500
19	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
20	− 50	+ 66.5	+ 116.5	13,500	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900

21	+ 50	0	− 50	2,500	+ 50	0	0	+ 50	2,500	+ 50	− 66.5	− 133	− 83	6,900
22	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
23	+ 50	0	+ 50	2,500	+ 50	0	0	− 50	2,500	+ 50	− 66.5	− 133	− 83	6,900
24	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
25	+ 50	0	+ 50	2,500	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
26	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
27	+ 50	0	+ 50	2,500	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
28	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
29	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
30	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	0	0	+ 50	2,500
31	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
32	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	0	0	+ 50	2,500
33	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
34	+ 50	− 66.5	− 16.5	272	+ 50	0	0	+ 50	2,500	+ 50	0	0	+ 50	2,500
35	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	− 66.5	− 133	− 83	6,900
36	+ 50	− 66.5	− 16.5	272	+ 50	0	0	+ 50	2,500	+ 50	0	0	+ 50	2,500
37	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	+ 66.5	+ 133	+ 183	33,000
38	+ 50	0	+ 50	2,500	+ 50	0	0	+ 50	2,500	+ 50	0	0	+ 50	2,500
39	+ 50	− 66.5	− 16.5	272	+ 50	− 66.5	− 76.7	− 26.7	710	+ 50	+ 66.5	+ 133	+ 183	33,500
40	+ 50	0	+ 50	2,500	+ 50	0	0	+ 50	2,500	+ 50	0	0	+ 50	2,500
41	+ 50	− 66.5	− 16.5	272	+ 50	+ 66.5	+ 76.7	+ 126.7	16,000	+ 50	+ 66.5	+ 133	+ 183	33,500
42	+ 50	0	+ 50	2,500	+ 50	0	0	+ 50	2,500	+ 50	0	0	+ 50	2,500
43	+ 50	− 66.5	− 16.5	272	+ 50	+ 66.5	+ 76.7	+ 126.7	710	+ 50	+ 66.5	+ 133	+ 183	33,500
44	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	0	0	− 50	2,500
45	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
46	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	+ 66.5	+ 133	+ 83	6,900
47	− 50	+ 66.5	+ 16.5	272	− 50	+ 66.5	+ 76.7	+ 26.7	710	− 50	+ 66.5	+ 133	+ 83	6,900
48	− 50	0	− 50	2,500	− 50	0	0	− 50	2,500	− 50	+ 66.5	+ 133	+ 83	6,900

$\Sigma(\text{Current}^2) = 61{,}900.$
$48 \times 50^2 = 48 \times 2500 = 120{,}000.$
$\therefore$ C^2R is 51.5 per cent. of that of continuous current alone.

$\Sigma(\text{Current}^2) = 108{,}600.$
$\therefore$ C^2R is 90.3 per cent.

$\Sigma(\text{Current}^2) = 448{,}000.$
$\therefore$ C^2R is 373 per cent.

TABLE LX. (*See page* 320.)

Number of Conductor.	Current in Phase.				Current 30 Deg. Out of Phase. Cos. 30 Deg. = .866.					Current 60 Deg. Out of Phase. Cos. 60 Deg. = .500.				
	Continuous Current.	Alternating Current.	Resultant Current.	(Current)².	Continuous Current.	Alternating Current, not considering Power Factor.	Alternating Current ÷ .866.	Resultant Current.	(Current)².	Continuous Current.	Alternating Current, not considering Power Factor.	Alternating Current ÷ .500.	Resultant Current.	(Current)².
1	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
2	− 50	− 38.3	− 88.3	7800	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
3	− 50	+ 38.3	+ 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
4	− 50	− 38.3	− 88.3	7800	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
5	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
6	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
7	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	+ 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
8	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
9	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
10	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
11	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
12	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	+ 76.5	+ 153	+ 103	10,600
13	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
14	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	− 38.3	− 76.5	− 126.5	16,000
15	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
16	− 50	+ 76.5	+ 26.5	700	− 50	+ 76.5	+ 88.2	+ 38.2	1450	− 50	− 38.3	− 76.5	− 126.5	16,000
17	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
18	− 50	+ 76.5	+ 26.5	700	− 50	+ 38.3	− 44.1	− 94.1	8900	− 50	− 38.3	− 76.5	− 126.5	16,000
19	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	+ 38.3	+ 76.5	+ 26.5	700
20	− 50	+ 76.5	+ 26.5	700	− 50	− 38.3	− 44.1	− 94.1	8900	− 50	− 38.3	− 76.5	− 126.5	16,000

21	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	− 76.5	− 153	− 203	41,000
22	− 50	− 38.3	− 88.3	7800	− 50	− 38.3	− 44.1	− 94.1	8900	− 50	+ 38.3	− 76.5	− 126.5	16,000
23	− 50	+ 38.3	− 11.7	137	− 50	+ 38.3	+ 44.1	− 5.9	35	− 50	− 76.5	− 153	− 203	41,000
24	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
25	+ 50	+ 38.3	+ 88.3	7800	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
26	+ 50	− 38.3	+ 11.7	107	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
27	+ 50	+ 38.3	+ 88.3	7800	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
28	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
29	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
30	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
31	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
32	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 25.6	700
33	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
34	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
35	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	− 76.5	− 153	− 103	10,600
36	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	− 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
37	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
38	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
39	+ 50	− 76.5	− 26.5	700	+ 50	− 76.5	− 88.2	− 38.2	1450	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
40	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
41	+ 50	− 76.5	− 26.5	700	+ 50	+ 38.3	+ 44.1	+ 94.1	8900	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
42	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
43	+ 50	− 76.5	− 26.5	700	+ 50	+ 38.3	+ 44.1	+ 94.1	8900	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
44	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	− 38.3	− 76.5	− 26.5	700
45	+ 50	+ 38.3	+ 88.3	7800	+ 50	+ 38.3	+ 44.1	+ 94.1	8900	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
46	+ 50	− 38.3	+ 11.7	137	+ 50	− 38.3	− 44.1	+ 5.9	35	+ 50	+ 76.5	+ 153	+ 203	41,000
47	+ 50	+ 38.3	+ 88.3	7800	+ 50	+ 38.3	+ 44.1	+ 94.1	8900	+ 50	+ 38.3	+ 76.5	+ 126.5	16,000
48	− 50	− 38.3	− 88.3	7800	− 50	− 38.3	− 44.1	− 94.1	8900	− 50	+ 76.5	+ 153	+ 103	10,600
	Σ (Current²) = 76,900. ∴ C^2R is 64 per cent.				Σ (Current²) = 95,240. ∴ C^2R is 79.5 per cent.					Σ (Current²) = 451,700. ∴ C^2R is 376 per cent.				

= volts per winding = $100 \times 0.615 = 61.5$ volts.[1] Amperes per winding $\frac{3330}{61.5} = 54$ amperes (effective). In this analysis, which considers instantaneous values, a sine wave current curve has been assumed, working from the maximum value of $54 \times \sqrt{2} = 76.5$ amperes.

When the current is in phase with the electromotive force, the distribution of things for positions A and B respectively is as shown in the diagrams of Figs 368 and 369, on pages 314 and 315. There are 48 conductors, corresponding to two poles, and these are numbered from 1 to 48. Any 48 successive conductors will give the same result. The values and arrow-heads at the upper part of the lines representing the face conductors give the instantaneous values and directions of the currents corresponding to the instantaneous conditions. The figures and arrow-heads at the middle of these lines show the instantaneous values and directions of the resultant currents. These results are also set forth in Tables LIX. and LX., where a current from bottom to top is regarded as positive, and from top to bottom as negative. There are also given values for lagging currents, the results from which show a rapid rise in C^2R loss.

These results are summed up in Table LXI., the figures given being the average for positions A and B:—

TABLE LXI. — SHOWING PROPORTION OF ARMATURE C^2R LOSS TO THAT OF A SIMILAR ARMATURE IN A CONTINUOUS-CURRENT GENERATOR FOR THE SAME OUTPUT, ASSUMING 100 PER CENT. CONVERSION EFFICIENCY

Power Factor.	Per Cent.
1.00	58
0.87	85
0.50	375
0	∞

Some indefiniteness is introduced by the exact position and width of the brushes under the condition of power factor of unity, the results for this value being higher in proportion as the number of conductors per pole is low. But for the other values of the power factor, this

[1] The Estimation of the Electro-Motive Force in Rotary Converters, Tables of Values of the Ratio of the Alternating Voltage between Collector Rings to the Continuous-Current Voltage at the Commutator, and the Estimation of the Effect of the Pole Face Spread upon these Values, have already been given in the section on Formulæ for Electro-Motive Force. (See page 88 *ante*).

indefiniteness does not appear. It will be noted that, just before reaching the position of short circuit under the brush, the current is often the sum of the alternating and continuous currents.

Throwing the results into the above form brings out forcibly the fact that it is only for comparatively high power factors that the residual C^2R loss is so greatly decreased.

Single-Phase Rotary Converters

The winding is connected up to the commutator segments, exactly as

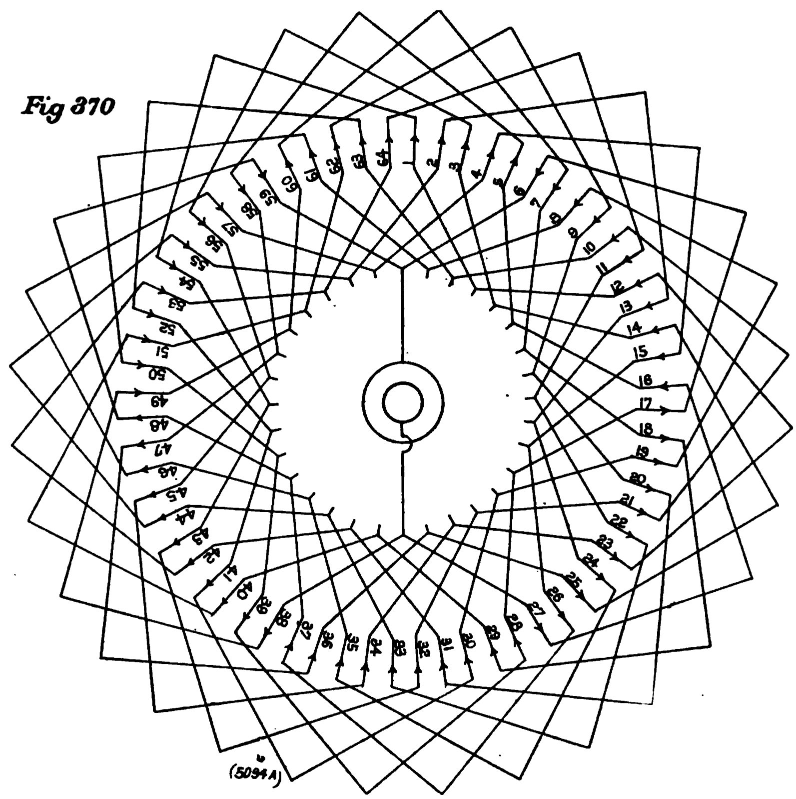


Fig. 370.—Winding for a Single-Phase Rotary Converter. Two-Circuit Single Winding with 64 Conductors, Six Poles, Pitch 11

for an ordinary continuous-current dynamo. For the alternating-current connections, the winding is tapped for a two-circuit winding, at some one point to one collector ring. Then, after tracing through one-half of the armature conductors, a tap is carried to the other collector ring. This case of a two-circuit single winding connected up as a single-phase rotary converter is illustrated in the winding diagram of Fig. 370, which relates to a six-pole armature with 64 conductors.

Fig. 371

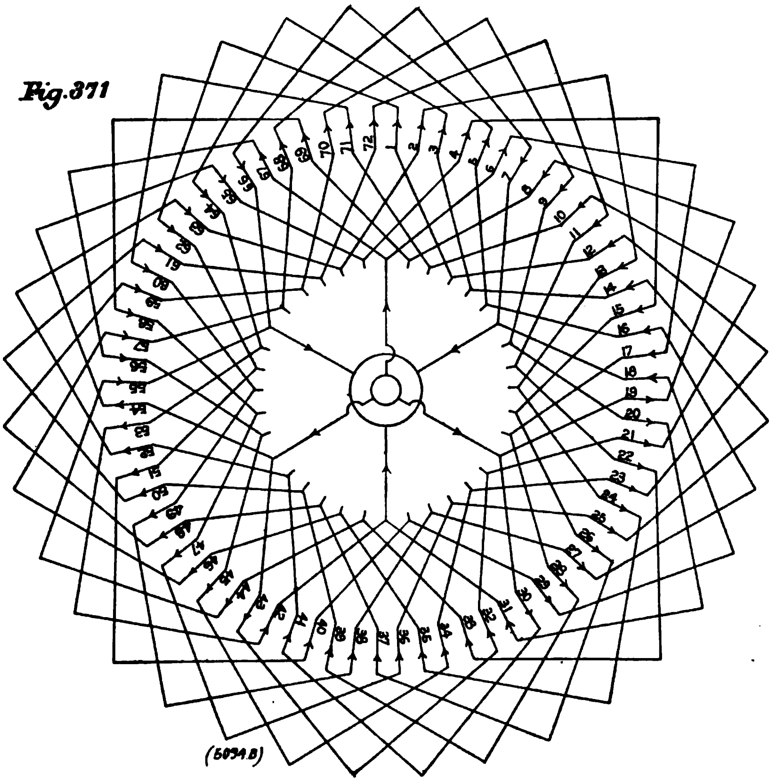


Fig. 371.—Winding for a Single-Phase Rotary Converter. Two-Circuit Singly Re-entrant triple Winding with 72 Conductors, Six Poles. Pitch 11

Fig. 372

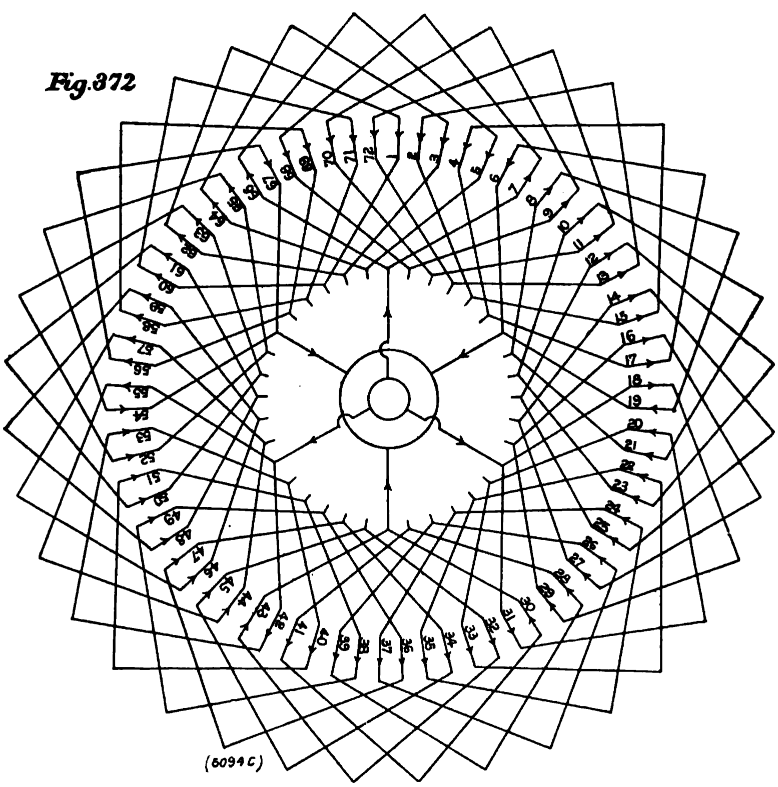


Fig. 372.—Winding for a Single-Phase Rotary Converter. Six-Circuit Single Winding with 72 Conductors, Six Poles, Front Pitch 13, Back Pitch 11

In Fig. 371 is given a diagram for a six-pole single-phase rotary converter, with a two-circuit singly re-entrant triple winding. This winding has 72 conductors. Single-phase rotary converters with two-circuit *multiple* windings, have two taps per winding, hence the two-circuit triple winding of Fig. 371 has 2 × 3 = 6 equi-distant taps.

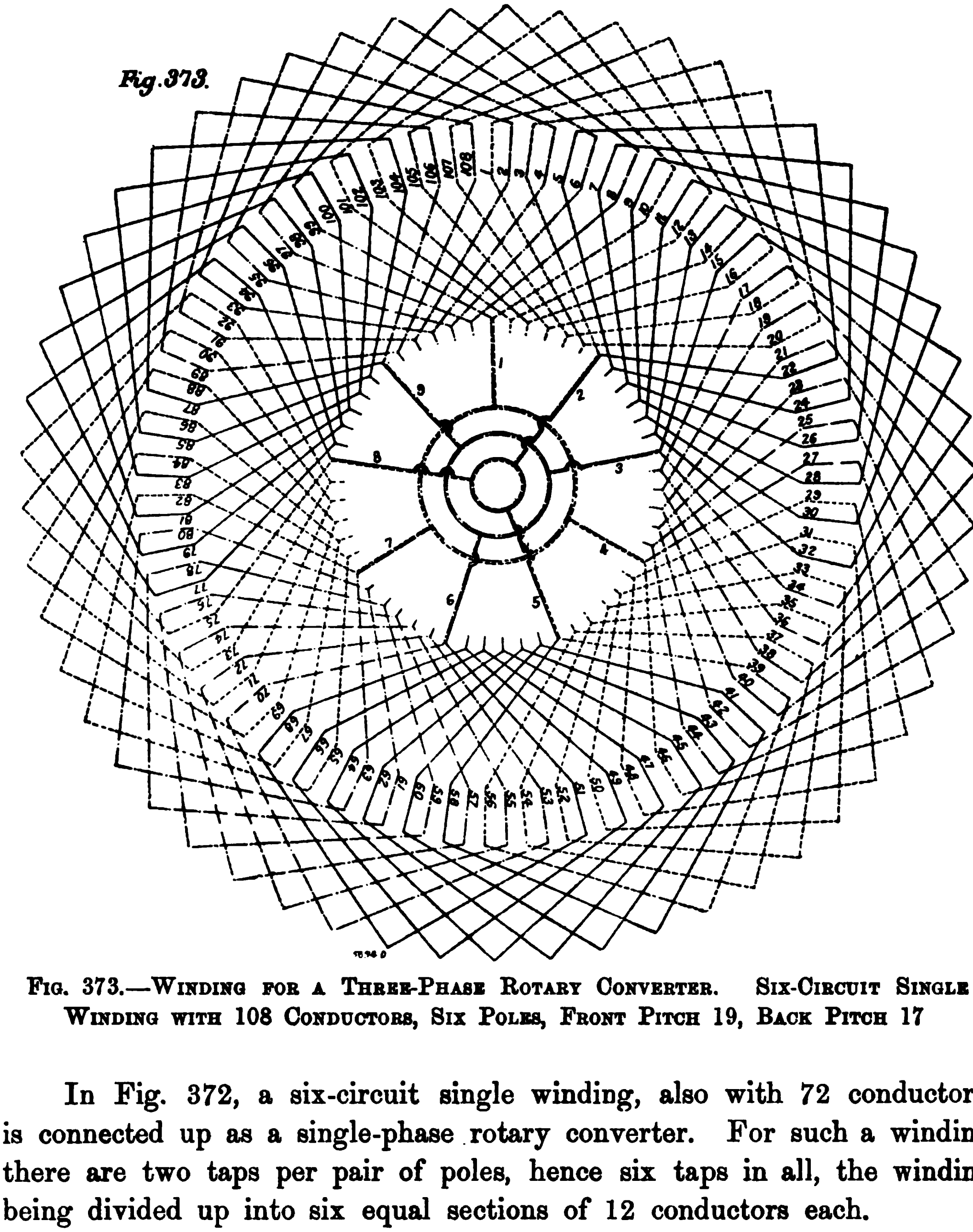


FIG. 373.—WINDING FOR A THREE-PHASE ROTARY CONVERTER. SIX-CIRCUIT SINGLE WINDING WITH 108 CONDUCTORS, SIX POLES, FRONT PITCH 19, BACK PITCH 17

In Fig. 372, a six-circuit single winding, also with 72 conductors, is connected up as a single-phase rotary converter. For such a winding there are two taps per pair of poles, hence six taps in all, the winding being divided up into six equal sections of 12 conductors each.

In single-phase rotary converters, the overlapping of the commutator

and collector-ring currents is so much less complete than for multiphase, as shown on pages 310 and 311, Tables LVII. and LVIII., as to render their use very uneconomical, because of the reduced output in a given machine. There is the further disadvantage that a single-phase rotary cannot be run up to synchronism from the alternating-current side.

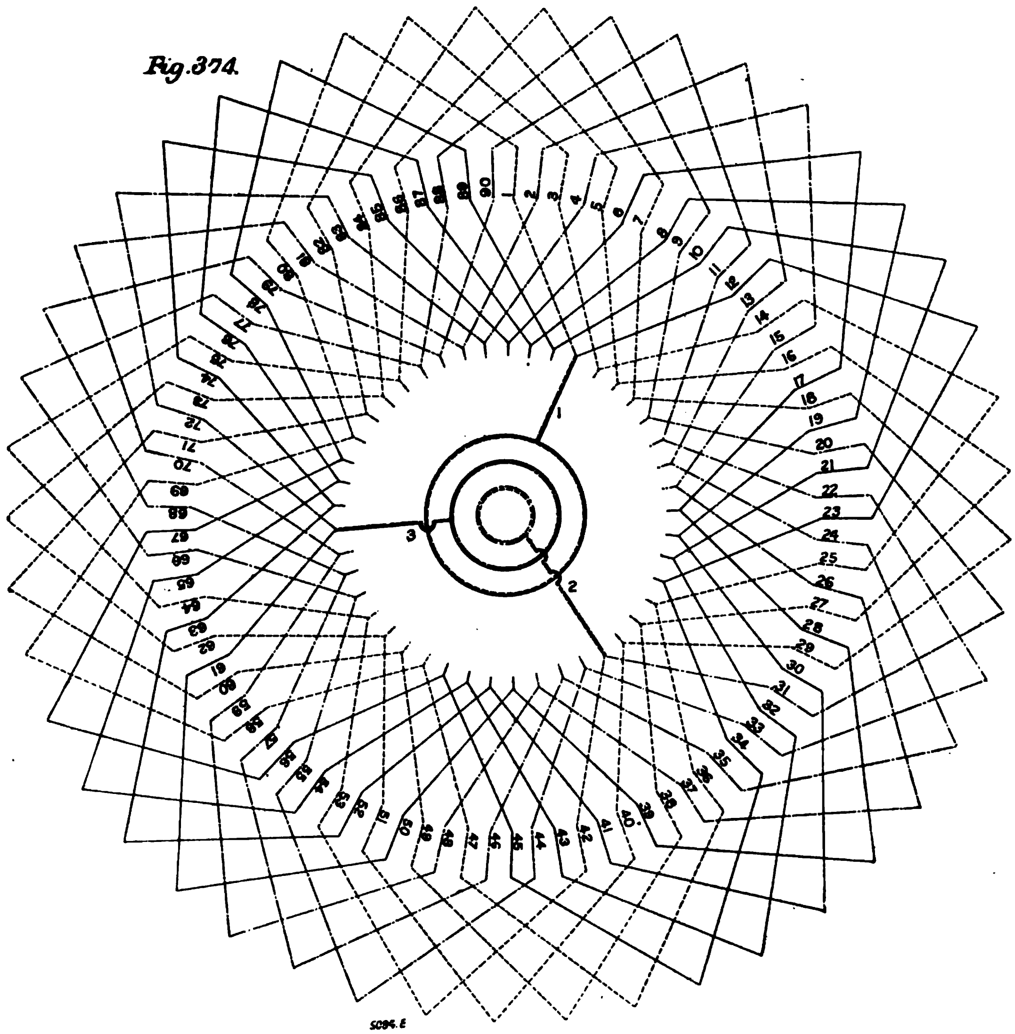


FIG. 374. WINDING FOR A THREE-PHASE ROTARY CONVERTER. TWO-CIRCUIT SINGLE WINDING WITH 90 CONDUCTORS, EIGHT POLES, PITCH 11

In general, the operation of single-phase rotary converters is distinctly unsatisfactory, and they are rarely used except for small capacities. An examination of the windings shows that, owing to the distribution of the conductors over the entire peripheral surface, the turns in series between collector rings are never simultaneously linked with the entire magnetic

flux ; in fact, such a winding used as a pure alternating current single-phase generator gives but 71 per cent. as great a voltage at the collector rings as the same machine used as a continuous-current dynamo would give at the commutator.[1] The ratio of the outputs, under such conditions, is for equal loads in the armature conductors, 71 : 100. It will be seen in

Fig. 375

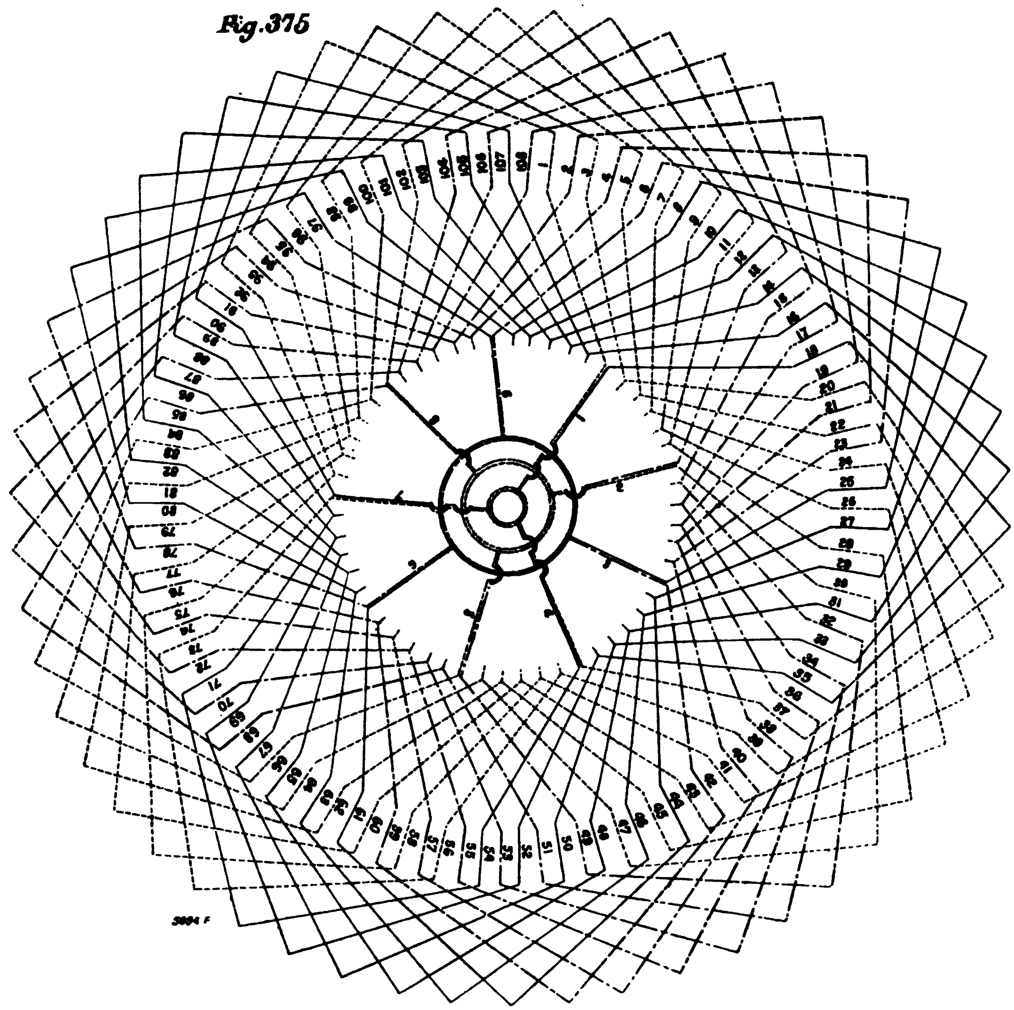


Fig. 375. Winding for a Three-Phase Rotary Converter. Two-Circuit Singly Re-entrant Triple Winding with 108 Conductors, Six Poles, Pitch 17

the following that this is largely avoided when the winding is subdivided for polyphase connections, and the relative advantages of these different polyphase systems is largely dependent upon the extent to which they are free from this objection.

[1] A discussion of the ratio of commutator and collector-ring voltages in rotary converters has already been given on pages 88 to 90, in the section relating to Formulæ for Electromotive Force.

Three-Phase Rotary Converters

The earlier rotaries were generally operated as three-phasers, the output for a given C^2R loss in the armature winding being 38 per cent. greater than for the same armature as used in a continuous-current

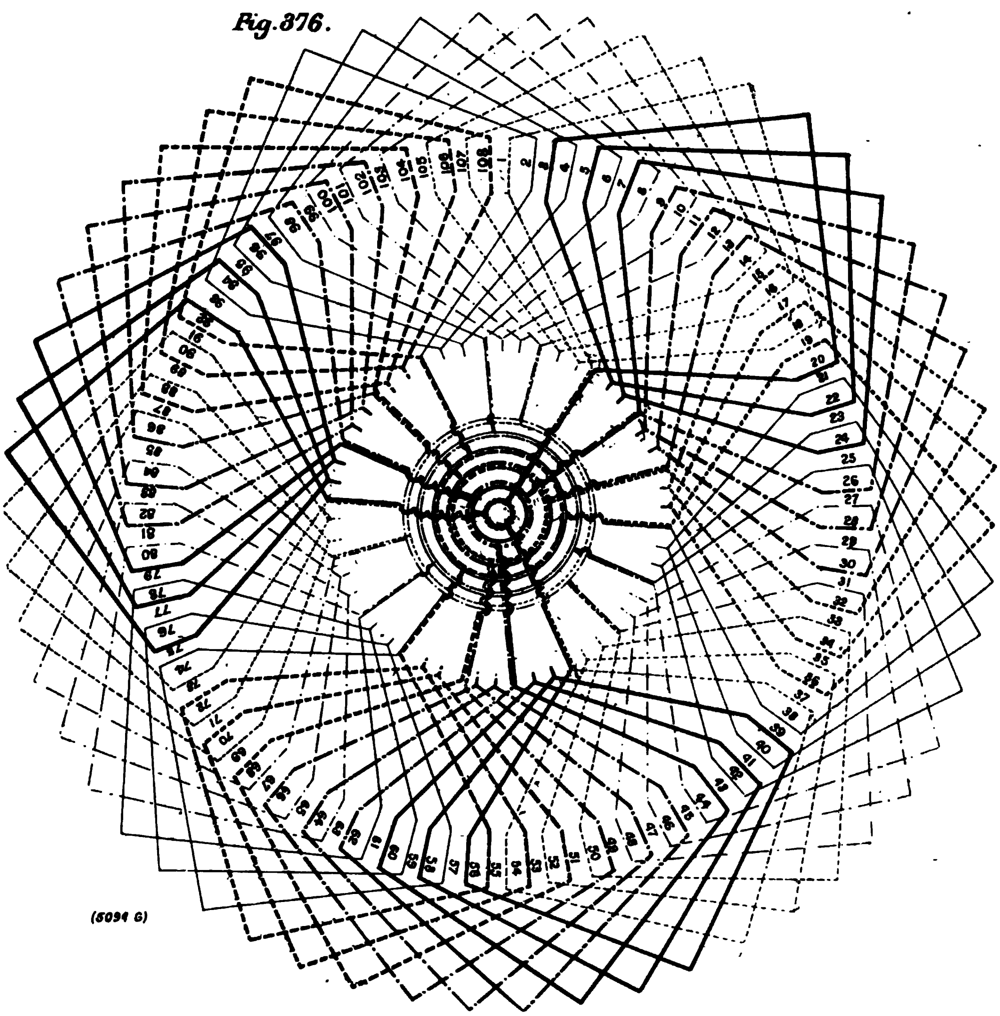


Fig. 376.—Winding for a Six-Phase Rotary Converter. Six-Circuit Single Winding with 108 Conductors, Six Poles, Pitch, Front 19, Back 17

generator. To-day, however, most rotaries are being arranged to be operated either as four or six-phasers, with the still further advantages of 67 per cent. and 98 per cent. increased output respectively, for a given heating in the armature conductors. These are the values given in Table LVII., page 310.

For three-phase rotary converters, there are three sections per pair of poles in multiple-circuit single windings, and three sections per pair of poles per winding in multiple-circuit multiple windings. There are three sections per winding, regardless of the number of pairs of poles

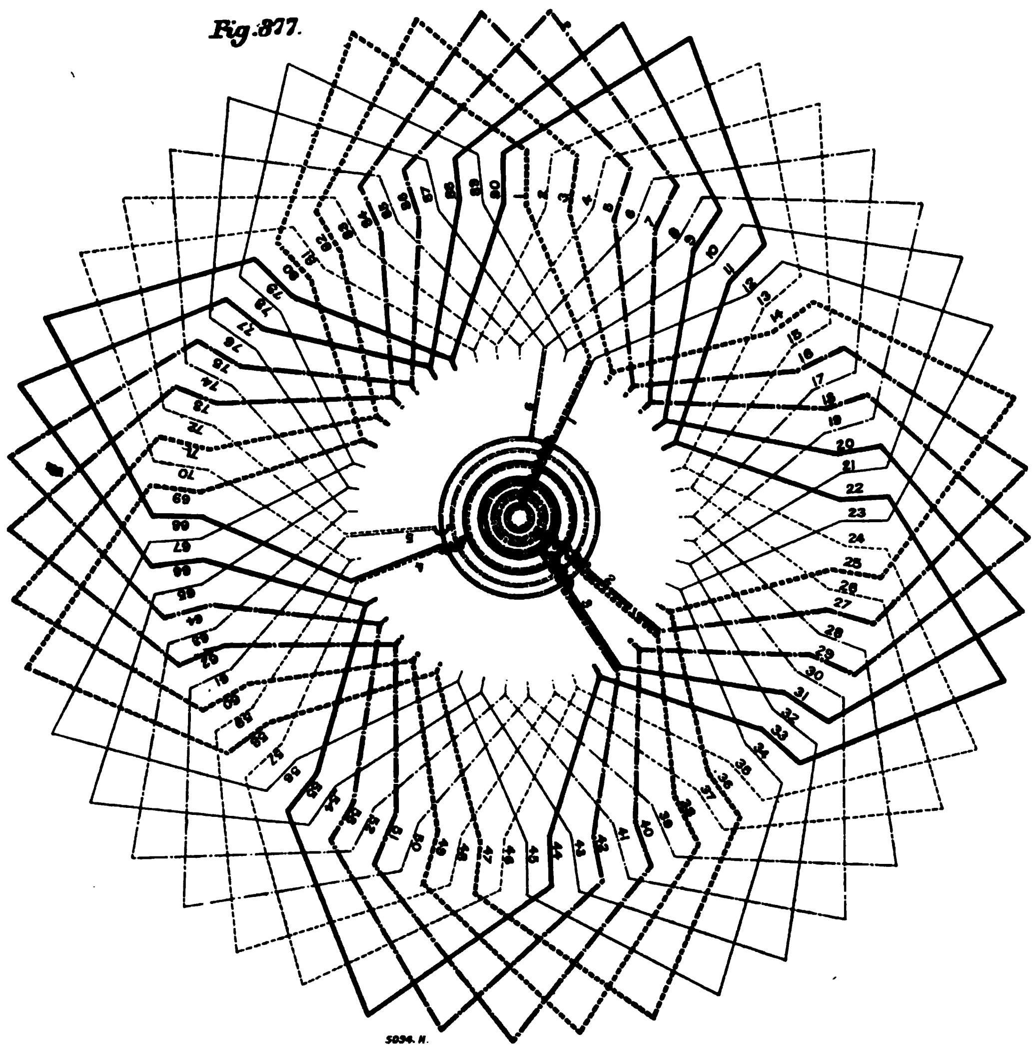


FIG. 377. WINDING FOR A SIX-PHASE ROTARY CONVERTER. TWO-CIRCUIT SINGLE WINDING WITH 90 CONDUCTORS, EIGHT POLES, PITCH 11

in two-circuit windings. Thus, a six-pole machine with a six-circuit triple winding would have $\frac{6}{2} \times 3 = 9$ sections. At equal ninths through the winding from beginning to end, leads would be carried to collector rings, three leads to each of the three collector rings. But if the armature had had a two-circuit double winding, there would have been

but three sections per winding, regardless of the number of poles; hence, for this two-circuit double winding there would be $2 \times 3 = 6$ sections, and six leads to the three collector rings. In Figs. 373 to 375, on pages 323 to 325, are given diagrams of three-phase rotary converter

Fig. 378.

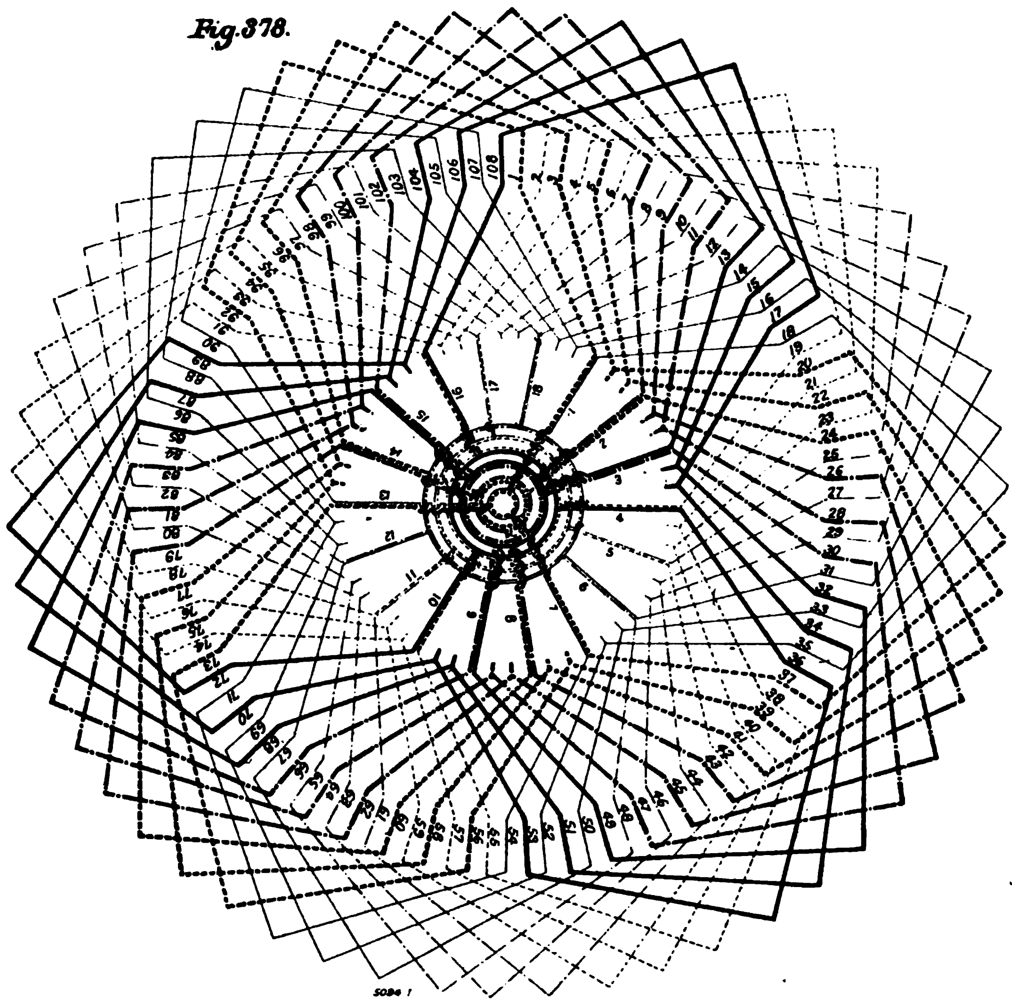


FIG. 378. WINDING FOR A SIX-PHASE ROTARY CONVERTER. TWO-CIRCUIT SINGLY RE-ENTRANT TRIPLE WINDING WITH 108 CONDUCTORS, SIX POLES, PITCH 17

windings, from a study of which familiarity with the inherent characteristics of such windings may be obtained. The most distinctive characteristic is the overlapping distribution of the conductors of the three phases, in consequence of which any one portion of the periphery of the armature carries conductors belonging to two phases. At one portion the conductors will belong alternately to phases 1 and 2, then to 2 and 3, and then to

3 and 1, then again to 1 and 2, the repetition occurring once per pair of poles. As a consequence of this property, the conductors of any one phase are distributed over two-thirds of the entire periphery; and when the width of the magnetic flux exceeds one-third of the polar pitch—and it is generally, when spreading is considered, at least three-quarters of the polar pitch—*all* the turns of one phase will not be simultaneously linked with the entire flux; the consequence is a lower alternating-current voltage per phase than if simultaneous linkage of all the turns of one phase with the entire flux occurred. Hence, for a given heating the output is limited, although being 56 per cent. higher than for single-phase rotaries, by reason of more effective linkage of turns and flux.

Six-Phase Rotary Converter

This disadvantage is mainly overcome in the so-called six-phase rotary converter, in which—as will appear later—the conductors of any one phase

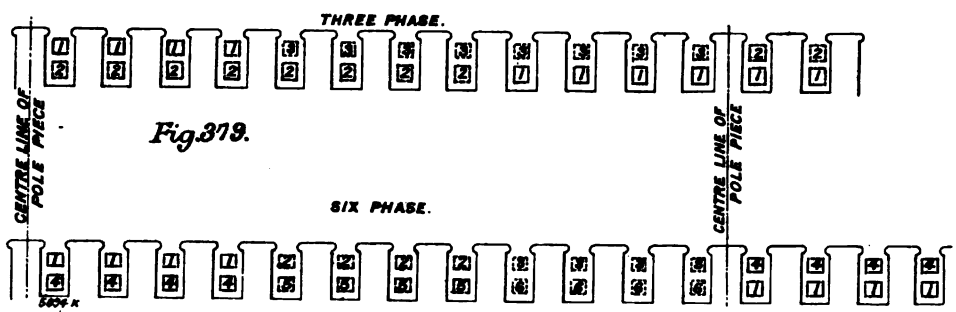


Fig. 379. Diagram of Rotary Converter Winding

are distributed over only one-third of the entire periphery, as a result of which an almost simultaneous linkage of all the turns of one phase with the entire magnetic flux is obtained. The resultant output of such a machine, for a given heating of the armature conductors, increases, as stated in Table LVII., on page 310, in the ratio of 1.38 to 1.98, *i.e.*, by 44 per cent. beyond that of an ordinary three-phase machine. As a matter of fact, this so-called six-phase is only a special case of three-phase arrangement. This distinction will be subsequently made clear.

Figs. 376 to 378, pages 326 to 328, are the same winding diagrams as for Figs. 373 to 375, pages 323, 324, and 325, but with the connections made for so-called "six-phase," with six collector rings. This requires in each case subdividing the winding up into just twice as many sections as for the case of three-phase windings. A study of these windings will

show that with these connections with six sections (where before there were three), the first and fourth, second and fifth, and third and sixth, taken in pairs, give a distribution of the conductors suitable for a three-phase winding, each of the above pairs constituting a phase. Furthermore, each portion of the periphery is now occupied exclusively by conductors belonging to one phase, *i.e.*, the first and fourth groups, the second and fifth, or the third and sixth, and in this way is distinguished from the previously-described three-phase windings in which the phases overlapped.

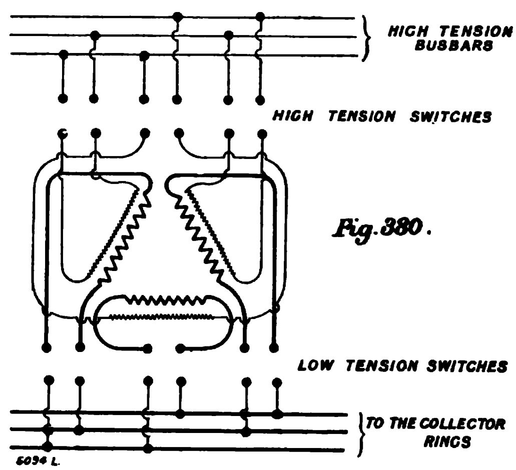


FIG. 380.—INTERCONNECTION OF STATIC TRANSFORMER AND ROTARY CONVERTER

This distinction will be made more clear by a study of the diagram given in Fig. 379.

INTERCONNECTION OF STATIC TRANSFORMERS AND ROTARY CONVERTERS

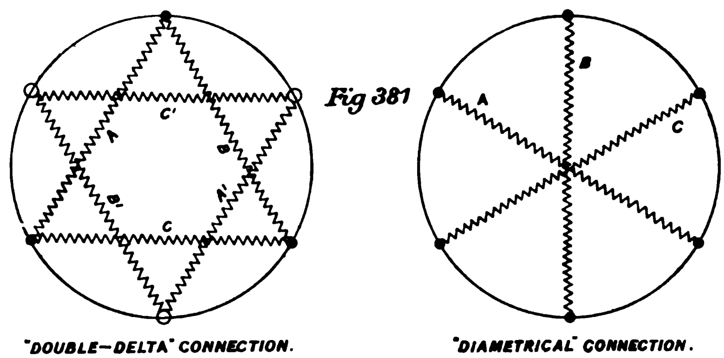
For three-phase rotary converters, the transformers should preferably be connected in "delta," as this permits the system to be operated with two transformers in case the third has to be cut out of circuit temporarily for repairs.

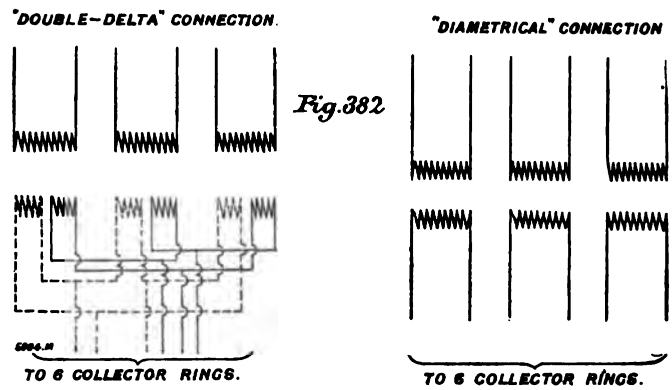
A satisfactory method of connection is given in Fig. 380.

For six-phase rotary converters, either of two arrangements will be satisfactory. One may be denoted as the "double-delta" connection, and the other as the "diametrical" connection. Let the winding be represented by a circle (Fig. 381), and let the six equidistant points on the circumference represent collector rings, then the secondaries of the transformers may be connected up to the collector rings in a "double-delta," as in the first

diagram, or across diametrical pairs of points as in the second diagram. In the first case it is necessary that each of the three transformers have two independent secondary coils, as A and A[1], B and B[1], C and C[1], whereas in the second case there is need for but one secondary coil per transformer. The two diagrams (Fig. 382) make this clear.

In the first case, the ratio of collector ring to commutator voltage is the same as for a three-phase rotary converter, it simply consisting of two





FIGS. 381 AND 382. EXAMPLES OF ROTARY CONVERTER CONNECTIONS

"delta" systems. In the second case, the ratio is the same as for a single-phase rotary converter, it being analogous to three such systems.

TABLE LXII

Style of Connection for Six-Phase Rotary Converter.	Ratio of Collector Ring Voltage to Commutator Voltage.
Double-delta connection	0.612
Diametrical	0.707

The latter—the "diametrical"—connection, is, on the whole, to be

preferred. The higher voltage at the collector rings permits of carrying lighter cables about the station, in wiring up from the static transformers to the rotary converter. It also only requires two secondary leads to be brought out—per transformer—and it simplifies the switching arrangements.

A switchboard connection suitable for a plant with four, six-phase rotary converters is given in Fig. 383, where it is arranged that the synchronising shall be done on the high-tension side of the transformer. This method of synchronising avoids the necessity of six-bladed, heavy current, low-tension switches. The switches A and B are more for the purpose of connectors; the line circuits are intended to be made and broken by the high-tension, quick-break, switches C. Another feature of the arrangement shown is that it brings the entire alternating-current system to the left of the line L, and the entire continuous-current system to the right of the line L, thus keeping them entirely separate. The particular scheme shown has two independent sets of high-tension feeders coming to the two feeder panels illustrated.

In conclusion, it may be said that six-phase rotary converters have in practice been found to run stably, and have been free from surging and flashing. The six collector rings can hardly be said to constitute any serious disadvantage, and there is the already explained gain of 44 per cent. in output from the standpoint of the heating of the armature conductors. This latter is, of course, an important advantage; but it must be kept in mind that this gain does not apply to the commutator, which must be—for a given output—just as large for a six-phase rotary as for a three-phaser.

Four-Phase Rotary Converters

In Fig. 384, on page 334, is given a six-circuit single winding connected up as a four-phase rotary converter. Here we subdivide the winding into four sections per pair of poles—hence in this case $4 \times \frac{6}{2} = 12$ total sections, and four collector rings.

A two-circuit single winding connected up for a four-phase rotary converter is shown in Fig. 385, on page 335. It is subdivided into four sections; the rule for two-circuit windings used as four-phase rotary converters being that they shall have four sections per winding, independent of the number of poles. Hence, in the two-circuit triple winding shown in Fig. 386, page 336, the winding is subdivided into $4 \times 3 = 12$ sections. All these four-phase windings are characterised

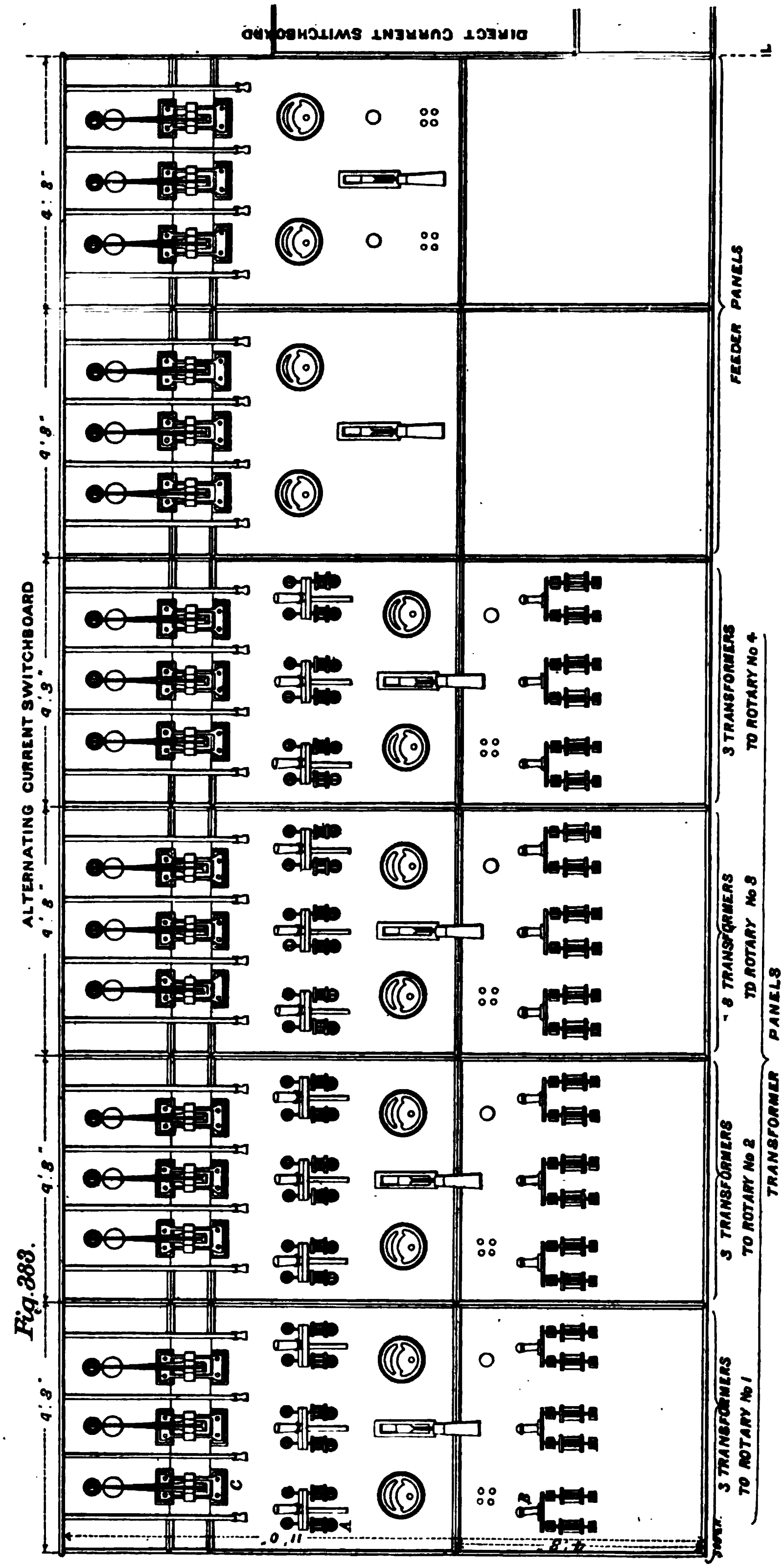


FIG. 383. SWITCHBOARD CONNECTION FOR FOUR SIX-PHASE ROTARY CONVERTERS

by the winding per phase having a spread of 50 per cent. of the polar pitch. Sections 1 and 3, as also 2 and 4, are really in the same phase; in this sense such rotary converters are sometimes called two-phase,

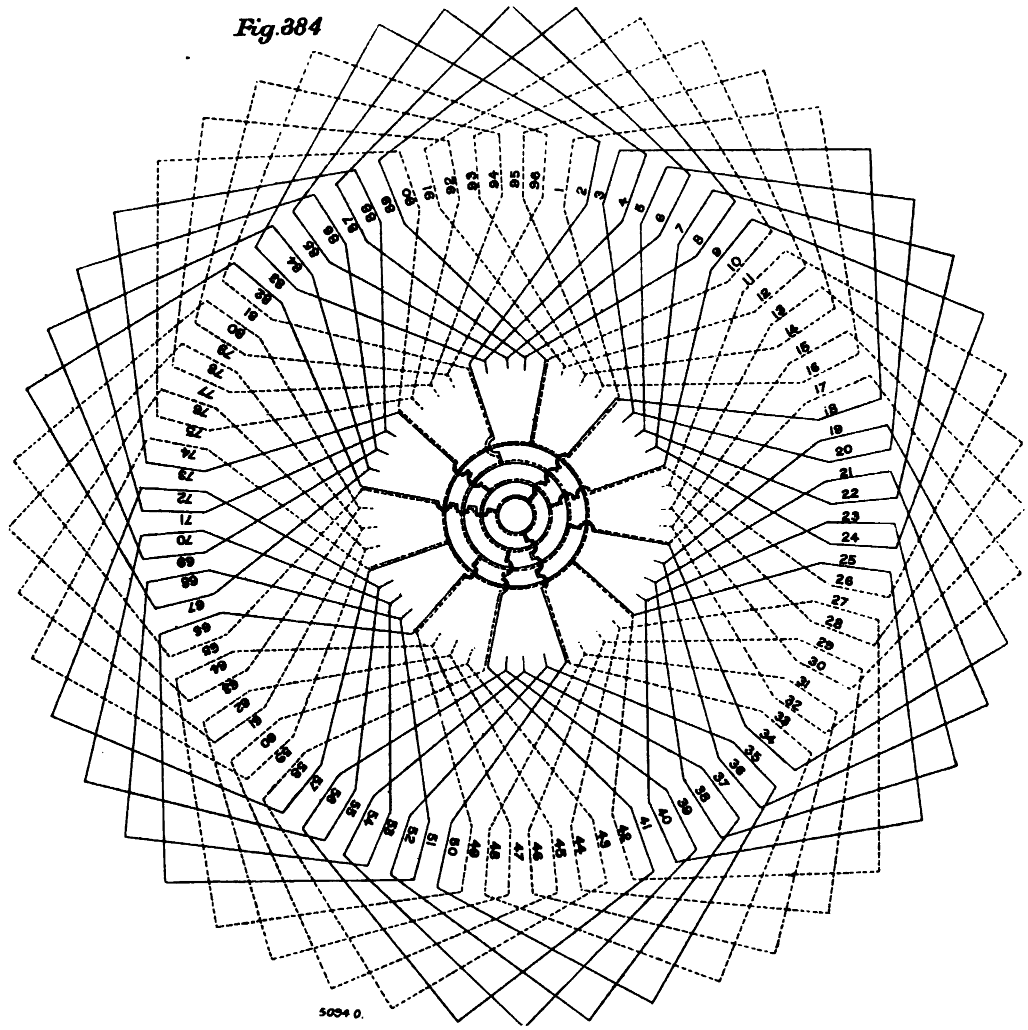


FIG. 384. WINDING FOR A FOUR-PHASE ROTARY CONVERTER. SIX-CIRCUIT SINGLE WINDING, WITH 96 CONDUCTORS, SIX POLES, PITCH 17 AND 15

also occasionally quarter-phase. The distribution is also well shown in Fig. 387, on page 336.

There are also in four-phase, as in six-phase, alternative methods of connecting from secondary transformer terminals to collector rings. The diametrical connection is to be preferred, and for the same reasons as in the case of six-phase.

TWELVE-PHASE ROTARY CONVERTERS

Another interesting combination of apparatus permits of obtaining the advantages of a 12-phase rotary converter with only two static transformers. Each transformer has one primary and four equal secondary

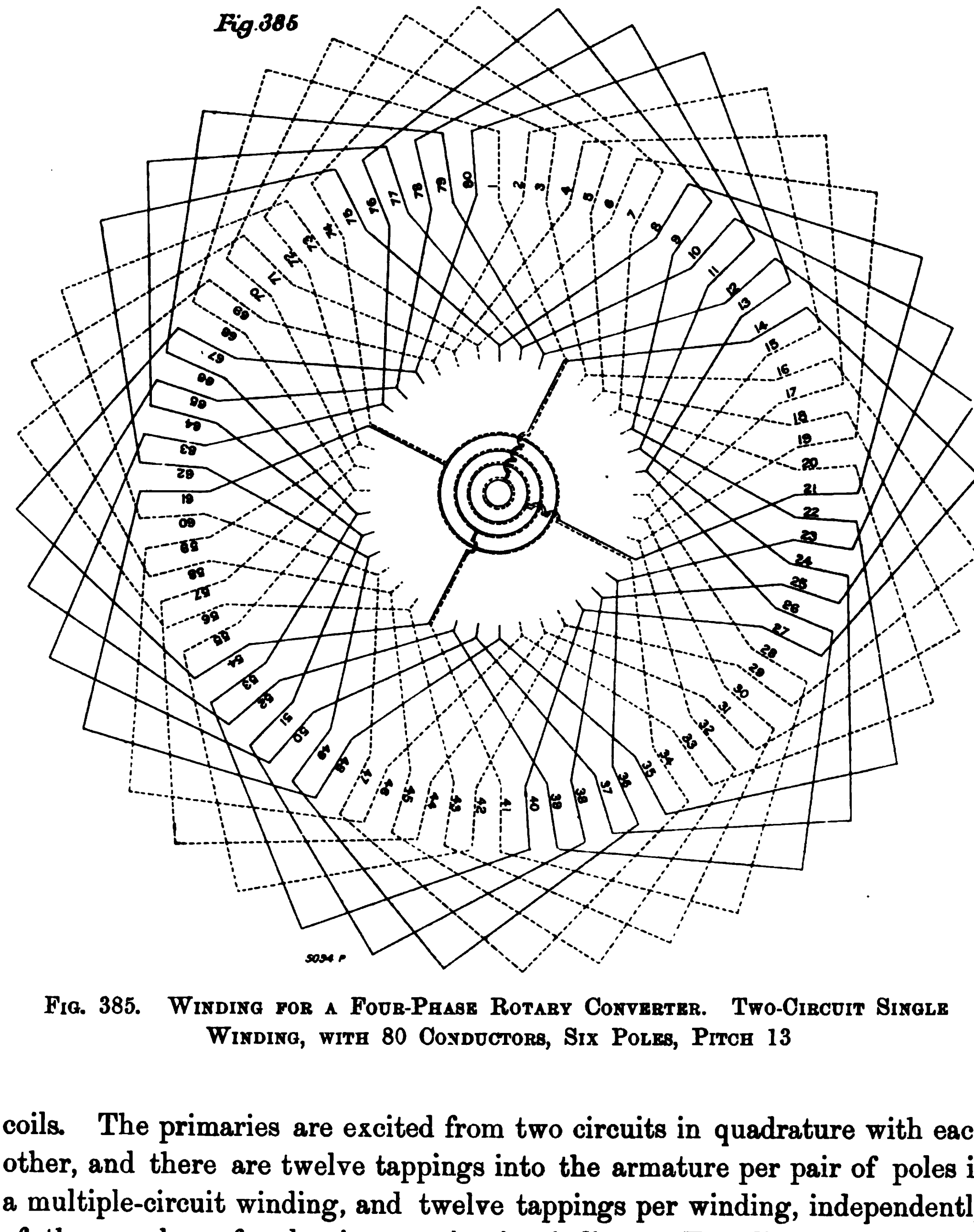


FIG. 385. WINDING FOR A FOUR-PHASE ROTARY CONVERTER. TWO-CIRCUIT SINGLE WINDING, WITH 80 CONDUCTORS, SIX POLES, PITCH 13

coils. The primaries are excited from two circuits in quadrature with each other, and there are twelve tappings into the armature per pair of poles in a multiple-circuit winding, and twelve tappings per winding, independently of the number of poles in two-circuit windings. The diagram, Fig. 388,

sets forth the underlying idea as applied to a bi-polar armature, the circle representing the winding, tapped at the points 1 to 12. Transformers I.

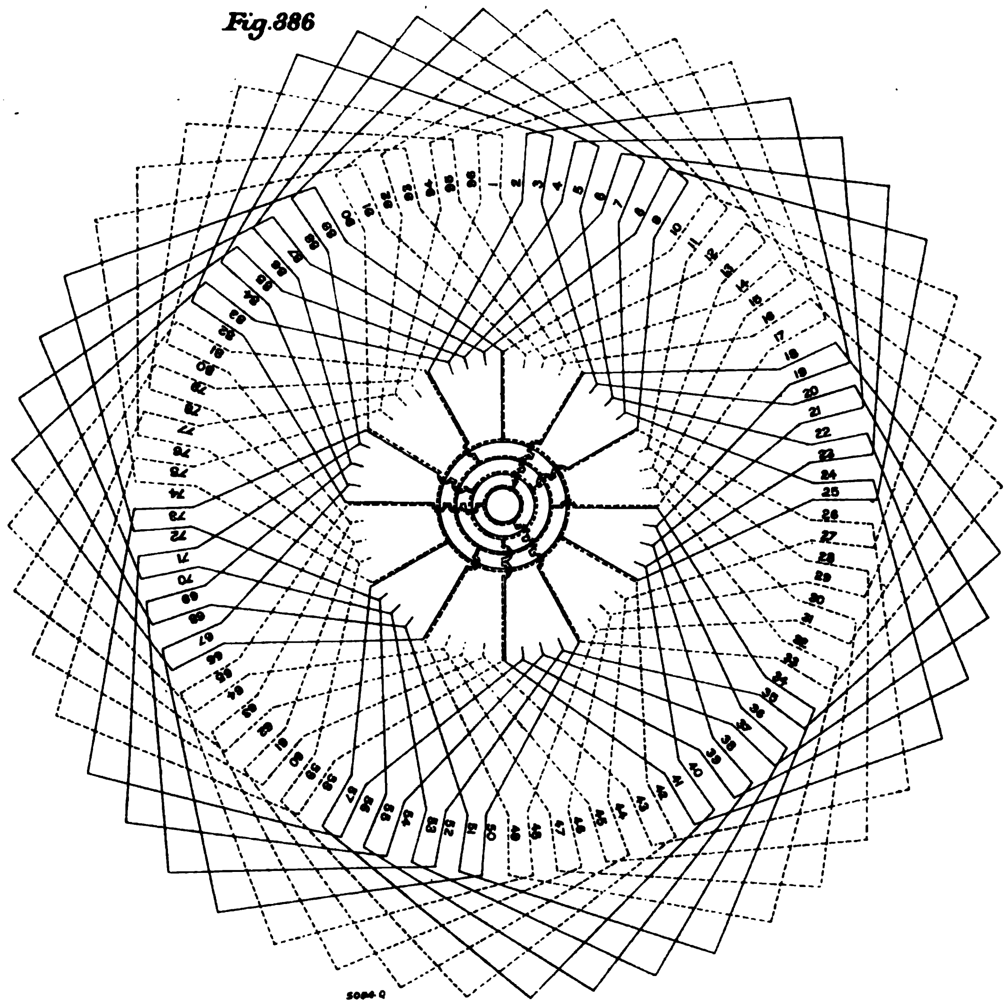


Fig. 386. Winding for a Four-Phase Rotary Converter. Two-Circuit Triple Winding, with 96 Conductors, Six Poles, Pitch 17

and II. have their primaries connected to circuits in quadrature with each other.

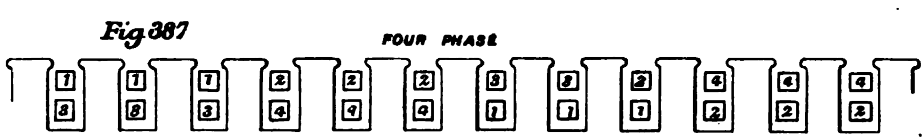
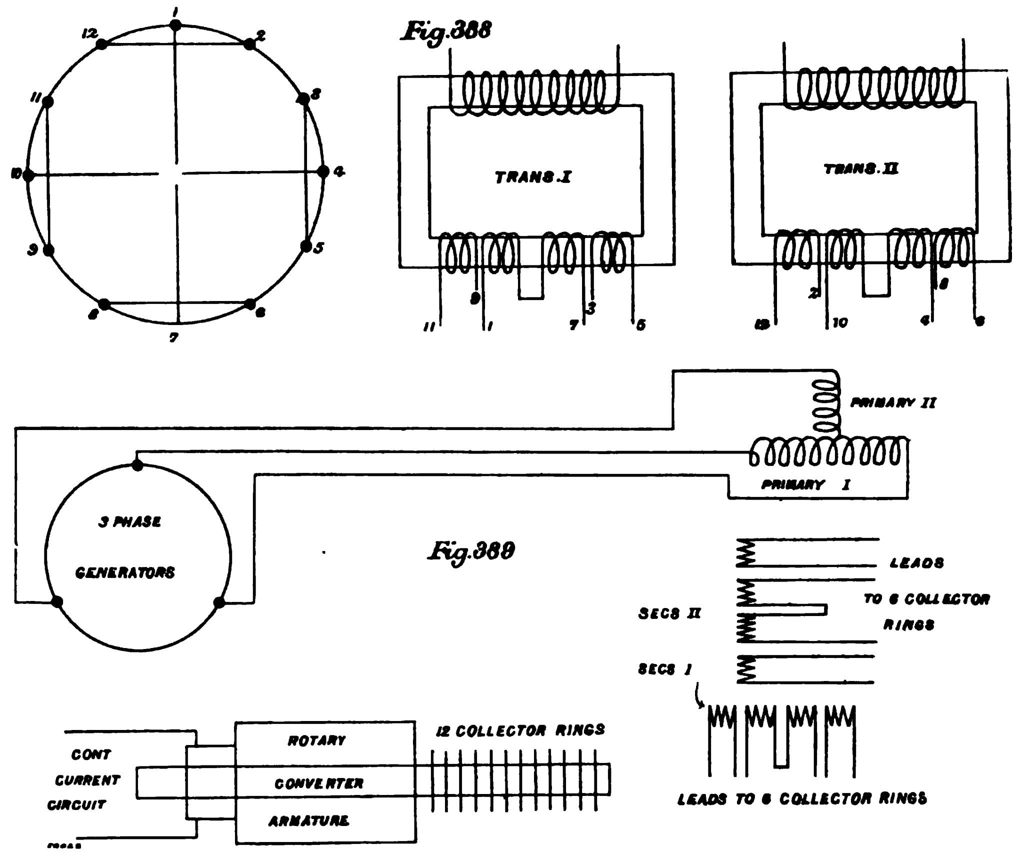


Fig. 387. Diagram Showing Distribution of Four-Phase Converter Windings

The 60 deg. chords represent the transformer secondaries 11-9, 3-5, 12-2, and 8-6, while the two diameters represent the series-connected

pairs of secondaries 1-7 and 10-4. Obviously the whole idea is based on two inscribed hexagons, the one standing at an angle of 90 deg. from the other. The four equally-wound secondary coils conform to the equality requirement between sides and radii.

By letting the transformer primaries have different windings, the well-known method of changing from three to quarter-phase permits of retaining the greater economy and other advantages of three-phase



FIGS 388 AND 389. DIAGRAM SHOWING CONVERTER WINDINGS AND CONNECTIONS

transmission, the further advantages of only two transformers per rotary, and a greatly increased output per rotary. This system is sufficiently indicated in diagram, Fig. 389.

DESIGN OF A SIX-PHASE 400-KILOWATT, 25-CYCLE, 600-VOLT ROTARY CONVERTER

The first question to decide is the number of poles. The periodicity being given, the speed will be inversely as the number of poles. High

speed, and hence as few poles as are consistent with good constants, will generally lead to the best results for a given amount of material.

In considering the design of continuous-current generators, it was shown that the minimum permissible number of poles is determined by the limiting armature interference expressed in armature ampere turns per pole-piece, and by the reactance voltage per commutator segment, for which, in the very first steps of the design, the average voltage per commutator segment is taken. But in polyphase rotary converters, the superposed motor and generator currents leave a very small resultant current in the armature conductors, and in six-phase rotary converters this is so small that armature interference would not be a limiting consideration; in fact, as many turns per pole-piece will be used on the armature as other considerations, first among which is that of permissible peripheral speed, shall determine. As the motor and generator currents cancel each other to a very considerable extent, the conductors have only to be of relatively small cross-section in order to carry the resultant current; nevertheless, by the time each conductor is separately insulated, no extraordinarily large number can be arranged on a given periphery, and hence no excessive armature interference can result. With insufficiently uniform angular velocity per revolution of the generator supplying the rotary converter, this assertion could not safely be made. In such a case, the pulsations of the motor component of the rotary converter current, caused by the inability of the rotary converter to keep in perfect step with the generator, and by the consequent oscillatory motion superposed upon its uniform rate of revolution, greatly decrease the extent to which the motor and generator components neutralise one another, and hence there results a large and oscillatory armature interference. But where a satisfactory generating set is provided, armature interference in the rotary converter is not a limiting consideration.

The reactance voltage of the coil under commutation must be made as low as possible, as in rotary converters one has a kind of "forced commutation;" in other words, one does not make use of a magnetic field to reverse the current in the short-circuited coil. The brushes remain at the neutral point for all loads, since any alteration in their position from the neutral point would interfere with the proper superposition of the collector ring and commutator currents. Moreover, the collector ring current must continue independently of the commutation going on in the generator component of the resultant current. The process

is complicated, and for practical purposes it appears desirable to estimate a nominal reactance voltage based upon that which would be set up in the short-circuited turns by the reversal of the continuous-current component.

The diameter of the armature is chosen as large as is consistent with retaining the armature conductors in place, using a reasonable amount of

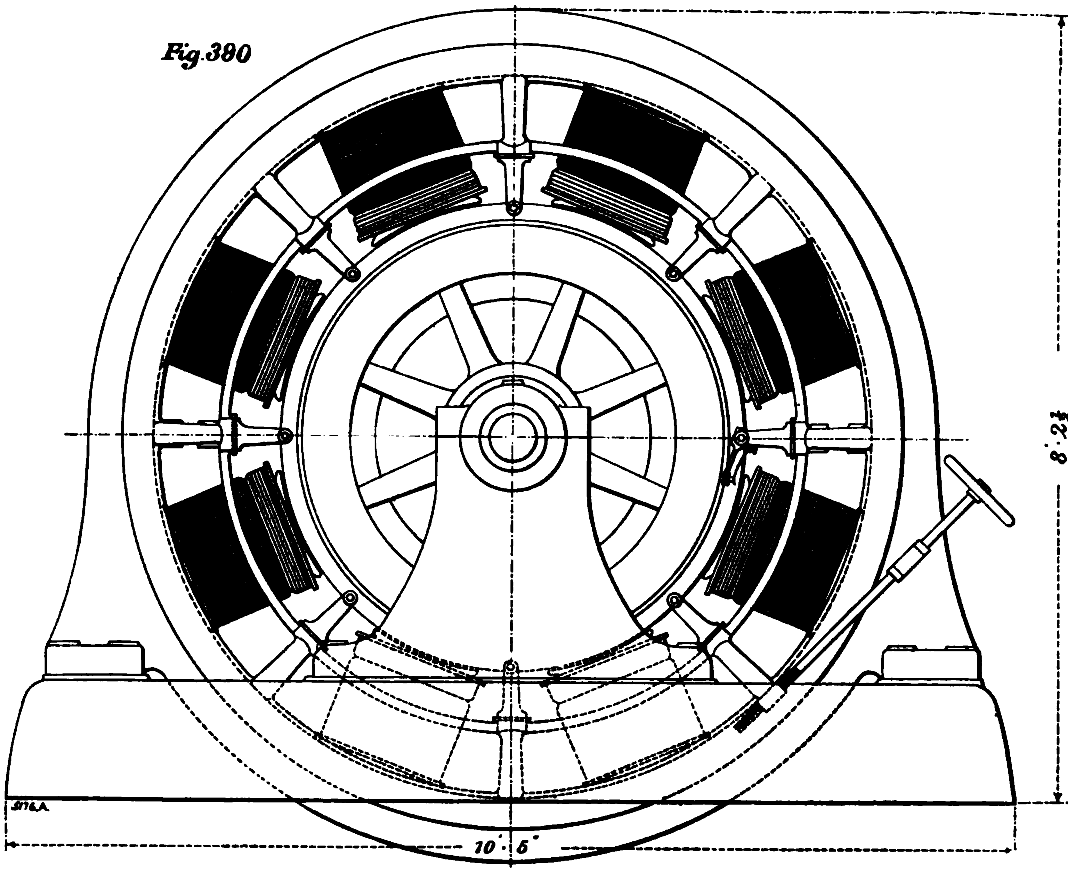


FIG. 390. EIGHT-POLE, SIX-PHASE, 400-KILOWATT, ROTARY CONVERTER

binding wire, figured with a conservative factor of safety. Upon this armature is generally placed as large a number of conductors as current and magnetic flux densities permit. For some ratings, however, a sufficiently low reactance voltage may be obtained without approaching extremes, either of armature diameter or of number of armature conductors. Another limitation often met with in rotary converter design is that of width of commutator segment at the commutator face. It is not desirable, on machines of several hundred kilowatts output, that the commutator

segments should be much less than $\frac{1}{4}$ in. in width. For a given diameter and number of poles, this at once restricts the number of commutator segments, and on the basis of one turn per commutator segment, also restricts the number of armature turns. For large rotary converters, two turns per segment would almost always lead to an undesirably high reactance voltage of the coil being commutated.

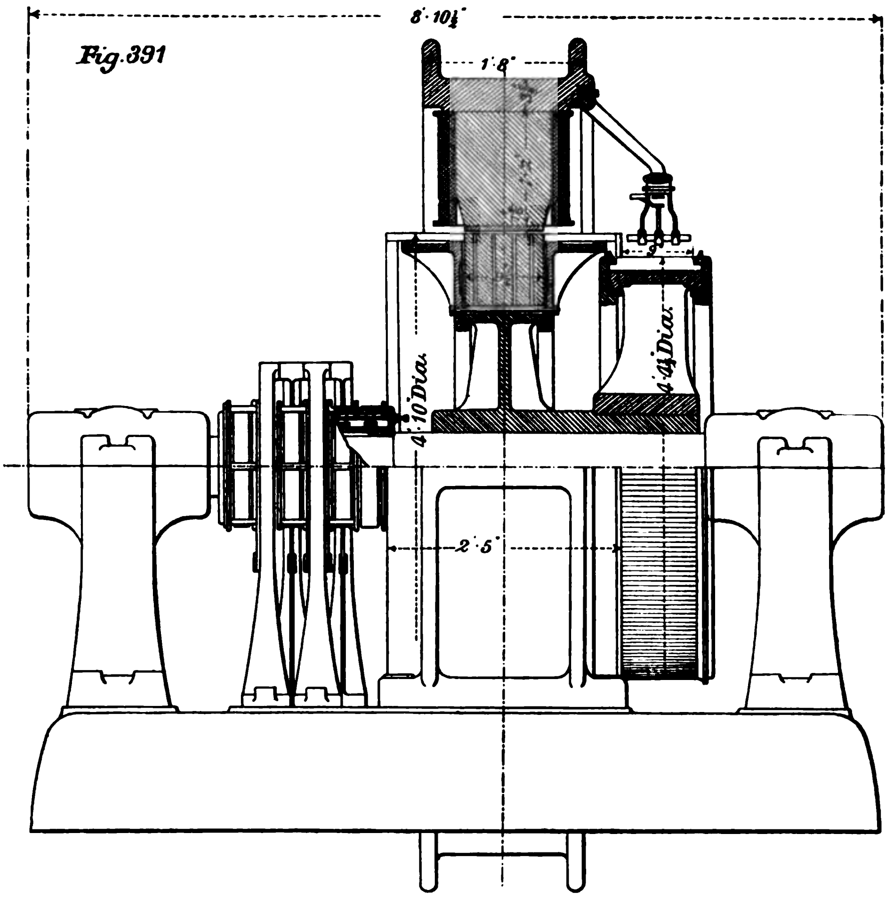
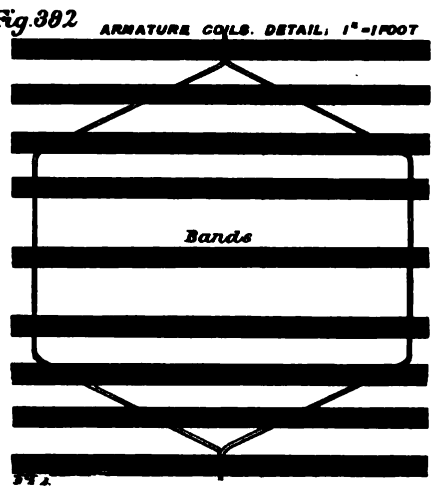


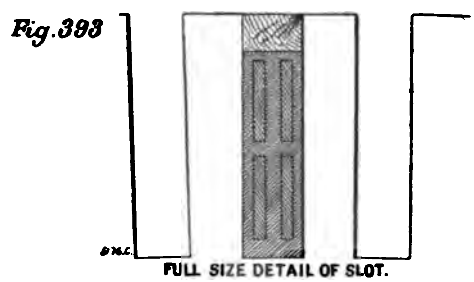
FIG. 391. EIGHT-POLE, SIX-PHASE, 400-KILOWATT ROTARY CONVERTER

The speed, expressed in revolutions per minute, is, in rotary converters, generally two or three times as high as for good continuous-current generators of the same output, and with an equal number of poles. Hence the frequency of commutation is also very high, often from 600 to 1000 complete cycles per second. Consequently, the inductance of the short-circuited coil must be correspondingly low, in order not to lead to high reactance voltage.

Rotary converters have been built with two commutators, in order

to escape the limitations referred to, of high peripheral speed and narrow commutator segments. This method is rather unsatisfactory, since the chief gain would be in connecting the two commutators in series; but by so doing, the entire current output has to pass through both, and the commutator losses are thereby doubled; while the cost of each commutator is so slightly reduced below that of one, as to render the construction expensive. A parallel connection of the two commutators at once sacrifices the chief gain, there only remaining the advantage of commutating half the current at each set of brushes; this, however, will not permit of very great reduction in the number of segments. Moreover, there is





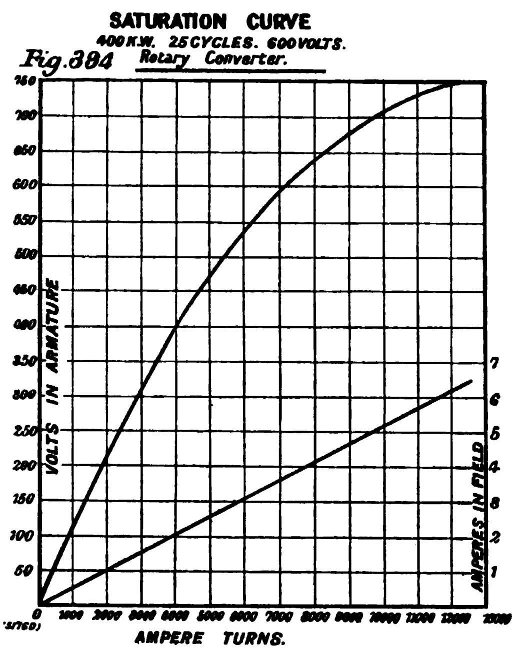
FIGS. 392 AND 393. DETAILS OF ARMATURE OF EIGHT-POLE, SIX-PHASE, 400-KILOWATT, ROTARY CONVERTER

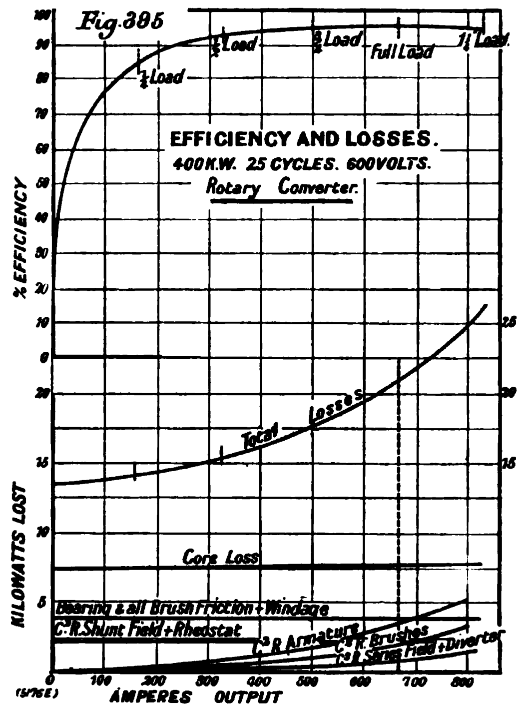
the further difficulty that unequal contact resistance at the brushes would bring about an unequal division of the load between the two windings.

In smaller rotary converters it sometimes becomes practicable to employ multiple windings (*i.e.*, double, or occasionally, even triple). In such cases, the tendency to increase the frequency of commutation must not be overlooked. If, for instance, one uses a double winding the calculation of the time during which one armature coil is short-circuited must be made with due regard to the fact that the two terminals of this coil are connected, not to adjacent but to alternative segments, and the intervening segment is, so far as time of short circuit is concerned, to be considered as a wide insulating gap. Hence, for a given width of brush, the time of short circuit is considerably reduced; but as the number of paths through the armature from the positive to the negative brushes has

been doubled, the current to be reversed is half what it would be for the equivalent single winding. No general conclusions, however, should be drawn, and the reactance voltage must be estimated for each particular case, from the inductance of the coil, the frequency of its reversal under the brush, and the current to be reversed.

In a similar manner, if one were comparing the relative advantages of, say, four and six poles, one should keep distinctly in mind that while





Figs. 394 and 395. Saturation and Efficiency Curves of Six-Phase, 400-Kilowatt, Rotary Converter

the final effect on the frequency of reversal may not be great (because of the inverse change in speed), the inductance per turn (largely dependent upon the length of the armature), may be quite different; and that the current to be reversed is, in the case of the larger number of poles, less than in the machine with few poles. It is much safer to make rather complete comparative calculations, as the probability of overlooking the effect of a certain change on all the constants involved is very considerable.

As a general rule, it is preferable to arrange the conductors in many slots, thus having but few per slot. It is also necessary to keep the

width of slot opening as small as possible; it should not be much, if any, greater than the radial depth of the air-gap. This is important, because laminated pole-faces should not be used where there is the least possibility of "surging," due to inconstant angular velocity per revolution of the generating set. In cases where this "surging" is present to any extent—with laminated pole-pieces—it will be diminished and sometimes prevented, if solid pole-faces of good conductivity, such as wrought-iron forgings of good quality, are used. The tendency of the superposed oscillations of the armature, and of the consequent variations in the magnetic field, is to set up induced currents in the pole-face, which produce reaction, and in turn tend to check these oscillations. The required result may be accomplished with minimum loss of energy, by suitably arranged copper circuits; but under favourable conditions the "surging" will be of small extent, and may be made negligible with but little dissipation of energy in the wrought-iron pole-faces. The magnet cores may be of cast steel; this, however, has not so high a specific conductivity as the best wrought iron, which latter should be employed for the pole-faces. The prevention of the surging will also be more complete the shorter the air-gap, but the high speeds of rotary converters generally render very small clearances undesirable.

Given the output, periodicity, and the voltage, trial calculations made with the foregoing various considerations in mind lead one very definitely to the choice of a certain number of poles, and the corresponding speed, which best combine good constants in operation with economy in material. At most, the choice will lie between two successive numbers of pairs of poles, in which case both designs should be thoroughly worked out, and the constants and costs compared.

For a six-phase rotary converter for 400 kilowatts output at 25 cycles, and 600 volts at commutator, the following design is worked out. The number of poles is eight, and the speed is 375 revolutions per minute, A good design with six poles and 500 revolutions per minute could have been obtained; and excellent practice in the application of these principles would be found in working out a corresponding specification for such a machine, then making a comparison of the costs of material.

The eight-pole design is illustrated in Figs. 390 to 393, on pages 339 to 341 inclusive, and in Figs. 394 and 395 are given the estimated saturation and efficiency curves.

Tabulated Calculation and Specification for a 400-Kilowatt Six-Phase Rotary Converter

Description

Number of poles	8
Kilowatt output	400
Speed, revolutions per minute	375
Terminal volts, full load	600
Amperes	667
Frequency (cycles per second)	25

Dimensions

Armature:

Diameter over all	58 in.
Length over conductors	29 ,,
Diameter of core at periphery	58 ,,
,, ,, bottom of slots	55½ ,,
,, ,, ,, laminations	40 ,,
Length of core over laminations	9½ ,,
Number of ventilating ducts	4
Width of each ventilating duct	⅜ in.
Effective length, magnetic iron	7.2 ,,
,, of core ÷ total length	0.76 ,,
Length round periphery	183 ,,
Pitch at surface	22.8 ,,
Insulation between sheets	10 per cent.
Thickness of sheets	0.014 in.
Depth of slot	1.25 ,,
Width of slot at root	0.28 ,,
,, at surface	0.28 ,,
Number of slots	300
Gross radial depth of lamination	9 in.
Radial depth below teeth	7.75 ,,
Width of teeth at root	0.303 ,,
,, ,, armature face	0.330 ,,
Size of conductor	0.05 in. × 0.45 in.
Magnet core, length of pole-piece	9.5 in. along shaft
Length of pole-arc	14 in.
Thickness of pole-piece at edge	1⅛ ,,

Pole-piece to consist of soft wrought-iron forging, so as to have maximum specific conductivity.

Pole-arc ÷ pitch	61 per cent.
Length of core, radial	14 in.
Diameter of magnet core	12 ,,
Bore of field	58½ ,,
Clearance	¼ ,,

Spool:

Length	14 in.
„ of shunt winding space	$11\frac{1}{4}$ „
„ of series „	$2\frac{3}{4}$ „
Depth of shunt „	2 „
„ of series „	2 „
„ of winding space...	2 „

Yoke:

Outside diameter	104 in. and $95\frac{1}{4}$ in.
Inside „	88 in.
Thickness	$3\frac{5}{8}$ „
Length along armature	20 „

Commutator:

Diameter	52.5 in.
Number of segments	600
„ „ per slot	2
Width of segments at surface	0.23 in.
„ „ at root	0.21 „
Total depth of segments	2 „
„ length of segment	11 „
Available length of segment	9 „
Width of insulation between segments	0.045 „

Collector:

Diameter	15 in.
Number of rings	6
Width of ring	2 in.
„ between rings	$\frac{7}{8}$ „
Length over all	22 „

Brushes:	Continuous Current.	Alternating Current.
Number of sets	8	6
„ in one set	4	3
Radial length of brush	$2\frac{1}{2}$ in.	
Width of brush	$1\frac{1}{2}$ „	1 in.
Thickness of brush	0.63 „	$\frac{1}{2}$ „
Dimensions of bearing surface, one brush ...	1.5 in. × 0.75 in.	1 in. × 1 in.
Area of contact, one brush	1.13 square inches	1 square inch
Type of brush...	Radial barbon	Copper

Insulation:

On core in slots	Oil-treated cardboard about .012 in. thick
Of conductor	Varnished linen tape

ELECTRICAL

Armature:

Terminal volts full load...	600
Total internal volts	614
Number of circuits	8
Style of winding	Multiple circuit drum
Times re-entrant	1
Total parallel paths through armature	8
Conductors in series between brushes	150
Type construction of winding	Bar
Number of face conductors	1200
„ slots	300
„ conductors per slot	4
Arrangement of conductors in slot	2 × 2
Number in parallel making up one conductor	1
Mean length of one armature turn	78 in.
Total number of turns	600
Turns in series between brushes	75
Length of conductor between brushes	5850 in.
Cross-section, one conductor	0.0225 square inch
„ eight conductors in parallel	0.18 „
Ohms per inch cube at 20 deg. Cent.	0.00000068
Per cent. increase in resistance 20 deg. Cent. to 60 deg. Cent.	16
Resistance between brushes, 20 deg. Cent.	0.022 ohm.
„ „ „ 60 deg. Cent.	0.0256

It has already been seen that in six-phase rotaries, 1.96 times the output may be taken from the commutator for the same C^2R loss in the armature conductors as in a continuous-current generator with the same winding. Hence, for a given load, the resultant current in the armature conductors is a little over half that delivered from the commutator. In the present machine, the full load output is 667 amperes. Allowing for efficiency, and not quite unity power factor, we may take the current in the armature conductors at $667 \times 0.55 = 370$ amperes.

C R drop in armature at 60 deg. Cent.	9.5 volts
„ series coils...	1 „
„ brush contact surface	2.2 „
„ not allowed for in above	1.3 in. cables and connections
Amperes per square inch, conductor	2050 figured on resultant current
„ „ brush-bearing surface	37 figured on current output from commutator.
„ „ shunt windings	980
„ „ series windings	1000

All but the armature current density and drop results are derived later in the specification, but are brought together here for reference.

Space Factor

In transformers, it is the aim to secure as high a ratio as possible of the total section of copper to the space in which it is wound, for a given specified insulation resistance. The same ratio, termed "space factor," is of service in proportioning the conductors and insulation to the armature slots.

Sectional area of slot $= 1.25 \times 0.28 = 0.35$ square inches.
„ „ copper in slot $= 4 \times 0.0225 = 0.09$ square inches.
"Space factor" $= 0.09 \div 0.35 = 0.26$.

i.e., 26 per cent. of the space is occupied by copper, and 74 per cent. by the necessary insulation.

Commutation:

Average volts between commutator segments	8
Armature turns per pole	75

Resultant current per conductor $= \dfrac{667 \times 0.55}{8} = 46$ amperes.

Resultant armature strength per pole $= 46 \times 75 = 3450$ ampere turns.

As the brushes remain at the mechanical neutral point, these exert only a distorting tendency, and do not have any demagnetising effect so long as the power factor of the alternating-current component is unity. It is also to be noted that, while the resultant armature current is 46 amperes, the 3450 corresponding ampere turns are by no means fully effective as magnetomotive force, being positive and negative in successive groups — sometimes even in successive turns — opposite one pole-piece. (See Figs. 368 and 369, pages 314 and 315.)

Determination of Reactance Voltage of Coil under Commutation

Diameter of commutator	52.5 in.
Circumference of commutator	165 „
Revolutions per second	6.25
Peripheral speed, inches per second	1030
Width of brush surface, across segments	0.75 in.
Time of one complete reversal	0.00073 secs.
Frequency of commutation, cycles per second	685
Coils short-circuited together per brush	3
Turns per coil...	1

Turns short-circuited together per brush	3
Conductors per group commutated together	6
Flux per ampere turn per inch gross length armature lamination	20
Flux through six turns carrying one ampere	1140
Inductance one coil of one turn	0.0000114 henrys
Reactance of one coil of one turn	0.049 ohm
Current in one coil (continuous-current component)	83.5 amperes
Reactance voltage, one coil	4.1 volts

Proportioning the Binding Wire

This is an important consideration in machines which must run at the high speeds customary with rotary converters. Cases might easily occur where an otherwise good machine might be designed; but on calculating the binding wire, it would be found to require a larger portion of the total peripheral surface than could properly be devoted to it.

Length of conductor between brushes ... ... $= 5850$ in.
Cross-section of conductor between brushes ... ... $\doteq 0.18$ square inch
Weight of armature copper $= 5850 \times 0.18 \times 0.32 = 340$ lb.

Every pound of material at the periphery is subject to a centrifugal force of 0.0000142 D N^2 pounds, where

D = diameter in inches.
N = revolutions per minute.

hence, in this case, to a force of

$$0.0000142 \times 58 \times 375^2 = 115 \text{ lb.}$$

The iron laminations are dovetailed into the spider, so the binding wire need only be proportioned to retain the weight of the copper wire in place.

Total centrifugal force $= 340 \times 115 = 39{,}000$ lb.

Force per square inch of armature surface $= \dfrac{39{,}000}{29 \times 58 \times \pi} = 7.4$ lb.

Total projected area $= 29 \times 58 = 1680$ square inches.

Total stress on binding wire $= 1680 \times 7.4 = 12{,}500$ lb., or 6250 lb. per side.

Using phosphor-bronze binding wire, and estimating on the basis of a tensile strength of 100,000 lb. per square inch, with a factor of safety of 10, we require

$$\frac{6250 \times 10}{100{,}000} = 0.63 \text{ square inch.}$$

Taking No. 12 Stubbs wire gauge with a diameter of 0.109 in, and cross-section of 0.00933 square inch, 72 of these would be required. These should be arranged in nine bands of eight turns each. Three of these bands should be over the laminated body of the armature, and three over each set of end connections. (See Fig. 392 on page 341.)

MAGNETIC CIRCUIT CALCULATIONS

Megalines *from* one pole at full load and 600 terminal volts (614 internal volts)	8.20
Coefficient of magnetic leakage	1.15
Megalines *in* one pole at full load	9.5
Armature :	
Core section = 7.75 × 7.2 × 2	= 112 square inches
Length, magnetic	7 in.
Density (kilolines)	73
Ampere turns per inch	20
Ampere turns...	140
Teeth :	
Number transmitting flux per pole piece	27
Section at face	64 square inches
" roots	60 "
Mean section	62 "
Length	1.25 in.
Apparent density (kilolines)	132
Width of tooth "*a*" (mean)	0.32
" slot "*b*"	0.28
Ratio "*a*" ÷ "*b*"	1.14
Corrected density	127
Ampere turns per inch	1100
Ampere turns...	1370
Gap :	
Section at pole-face	133 square inches
Length, one side	0.25 in.
Density at pole-face (kilolines)	61
Ampere turns (0.313 × 61,000 × 0.25)	4800
Magnet Core :	
Section	113 square inches
Length	14 in.
Density (kilolines)	84
Ampere turns per inch	50
Ampere turns...	700
Yoke :	
Section – 2 × 62	124 square inches
Length (per pole)	17 in.
Density (kilolines)	77
Ampere turns per inch	640

Summary of Ampere Turns

Armature core	140
„ teeth	1370
Gap ...	4800
Magnet core ...	700
Yoke	640
Total per spool	7650

Spool Windings

Shunt:

Mean length, one turn ...	3.66 ft.
Ampere turns per shunt spool, full load ...	7,650
Ampere feet ...	28,000
Radiating surface, one field spool	700 square inches
Watts per square inch to be allowed at 20 deg. Cent.	0.40
„ spool at 20 deg. Cent. ...	280
„ „ shunt winding at 20 deg. Cent.	220
„ „ series „ „ „	60
„ „ shunt winding at 60 deg. Cent.	255
Shunt copper per spool ...	110
Volts at terminals of spool at 20 deg. Cent.	56
Amperes per shunt spool	3.92
Turns „ „	1950
Total length of shunt conductor ...	7150 ft.
Resistance per spool at 20 deg. Cent.	14.4 ohms
Pounds per 1000 ft.	15.4 lb.
Size of conductor	No. 15 S.W.G.
Dimensions bare	0.072 in. in diam.
Dimensions double cotton covered	0.082 „ „
Cross-section ...	0.00407 sq. inches
Current density, amperes per square inch ...	980
Available winding space	10 in.
Number of layers	17
Turns per layer	115

Rotary converters do not run so well with much lag or lead, and the superposition of the motor and generator currents is far less perfect; but it is often found convenient to use a series coil of some 25 per cent. of the strength of the shunt coil, and to have, on the side of the machine, a switch, which when completely open sends all the main current, except a very small percentage, through the series winding, the small balance passing through a diverter rheostat. In the next position, about half of the current is diverted through the rheostat, the series coil being much weaker; and in the final position, the series coil is completely short-circuited, all the current being diverted from it. This enables the series

winding to be employed to the extent found desirable, considered with relation to the high-tension transmission line, as well as to the low-tension continuous-current system, on which latter system it is desirable to have the terminal voltage increase with the load.

By adjusting the shunt excitation so that the current lags slightly at no load, and by having sufficient series excitation, the total field strength increases as the load comes on, and thus controls the phase of the motor current. At some intermediate load the motor current will be exactly in phase with the electromotive force, and at higher loads will slightly lead, thus also maintaining rather higher commutator voltage.

Series:

Ampere turns, full load ...	2000
Full load amperes ...	667
Amperes diverted ...	167
,, in series spool ...	500
Turns per spool ...	4
Size of conductor used ...	2 in. by 0.05 in.
Number in parallel ...	5
Total cross-section ...	0.5 square inch
Current density, amperes per square inch ...	1000
Mean length of one turn ...	3.66 ft.
Total length, all turns on eight spools ...	1400 in.
Resistance of eight spools at 20 deg. Cent. ...	0.0019 ohm
Series C^2R watts, total at 20 deg. Cent. ...	475
,, ,, per spool at 20 deg. Cent. ...	60
,, ,, ,, 60 ,, ...	70
Weight of series copper ...	225 lb.

Calculations of Losses and Heating

Armature:

Resistance between brushes ...	0.0256 ohm at 60 deg. Cent.
C^2R loss at 60 deg. Cent. ...	3500 watts figured from resultant current
Frequency, cycles per second = C = ...	25
Weight of armature teeth ...	245 lb.
,, ,, core ...	2310 ,,
Total weight armature laminations = ...	2555 ,,
Apparent flux density in teeth (kilolines) ...	132
Flux density in core (kilolines) = D = ...	73
C.D. ÷ 1000 = ...	1.83
K = ...	1.65
$\frac{K.C.D.}{1000}$ = watts core loss per lb. = ...	3.02
Total core loss = 3.02 × 2555 = ...	7700 watts

Total armature loss = ...	11,200 watts
Armature diameter	58 in.
„ length	34 „
Peripheral radiating surface	5300 square inches
„ speed, feet per minute	5700
Watts per square inch in radiating surface...	2.1
Assumed rise of temperature per watt per square inch by thermometer, after 10 hours' run	20 deg. Cent.
Total rise estimated on above basis	42 „
Assumed rise of temperature per watt per square inch by resistance, after 10 hours' run	30 „
Total rise estimated on above basis	63 „

It will be observed that the total weight of iron in armature, *i.e.*, 2555 lb., is multiplied by the "watts core loss per pound" to obtain total core loss. This includes loss in teeth, as the curve (see Fig. 117, page 113) from which the constant was taken, is so proportioned as to allow for core and tooth losses for this type of construction and range of magnetic densities.

COMMUTATOR LOSSES AND HEATING

Area of all positive brushes	18 square inches
Amperes per square inch contact surface	37
Ohms per square inch contact surface, assumed	0.03
Brush resistance, positive and negative	0.0033
Volts drop at brush contacts	2.2
C^2R loss	1500 watts
Brush pressure	1.25 lb. per sq. in.
„ „ total	45 lb.
Coefficient of friction	0.3
Peripheral speed	5150 ft. per min.
Brush friction	70,000 ft.-lb. per min.
„ „	1600 watts
Stray watts lost in commutator, assumed	400
Total „ „	3500
Diameter of commutator	52.5 in.
Length „ „	9 „
Radiating surface	1500 square inches
Watts per square inch radiating surface	2.3
Assumed rise of temperature per watt per square inch after 10 hours' run	15 deg. Cent.
Total rise estimated on above basis	35 „

COLLECTOR LOSSES AND HEATING

Total contact area of all brushes...	18 square inches
Amperes per square inch contact surface	110
Ohms per square inch contact (assumed)	0.003

Total resistance of brushes per ring	0.001
Volts drop at brush contacts	0.034
C^2R loss at brush contacts per ring	110 watts
,, ,, ,, in six rings	660 ,,
Brush pressure, pounds per square inch	1.0
,, ,, total pounds	18
Coefficient of friction	0.3
Peripheral speed, feet per minute...	1470
Brush friction, foot-pounds per minute	8000
,, ,, watts lost	180
Total watts lost in collector	840
Diameter collector	15 in.
Effective length of radiating surface	12 ,,
Radiating surface	570 square inches
Watts per square inch radiating surface	1.5
Assumed rise of temperature per watt per square inch after 10 hours' run	20 deg. Cent.
Total rise estimated on above basis	30 ,,

SPOOL LOSSES AND HEATING

Spool:

C^2R loss at 60 deg. Cent. per shunt coil	255 watts
,, ,, per series coil	70 ,,
Total watts lost per spool	325 ,,
Length of winding space, total	14 in.
Circumference of spool	50 ,,
Peripheral radiating surface per spool	700 square inches
Watts per square inch radiating surface	.465
Assumed rise of temperature per watt per square inch by thermometer, after 10 hours' run	80 deg. Cent.
Total rise estimated on above basis	37 ,,
Assumed rise of temperature per watt per square inch by resistance, after 10 hours' run	120 ,,
Total rise estimated on above basis	56 ,,

EFFICIENCY

Output, full-load watts	400,000
Core loss	7,700
Armature C^2R loss at 60 deg. Cent.	3,500
Commutator losses	3,500
Collector losses	840
Shunt spools losses	2,040
,, rheostat losses	300
Series spools losses	560
,, diverter losses	190
Friction, bearings, and windage	2,000
Input, total	420,630
Commercial efficiency, full load	95 per cent.

Materials

Armature core	Sheet steel
„ spider	Cast iron
„ conductors	Copper
Commutator segments	„
„ leads	Rheotan
„ spiders	Cast iron
Pole-piece	Wrought-iron forging
Yoke	Cast steel
Magnet core	„
Brushes	Carbon and Copper
Brush-holder	Brass
„ yoke	Gun-metal
Binding wire	Phosphor bronze
Insulation, commutator	Mica
„ armature	Varnished linen tape

Weights

	Lb.	
Armature:		
Laminations	2,550	
Copper	340	
Spider	1,550	
Shaft	1,230	
Flanges	700	
Commutator:		
Segments	1,000	
Mica	80	
Spider	1,000	
Press rings	200	
Other parts	300	
Collector, complete	700	
Armature, commutator, collector, and shaft complete		9,650
Magnet:		
Cores	3,550	
Pole-pieces	400	
Yoke	5,000	
Field:		
Shunt coils	880	
Series „	225	
Total copper	1,105	
Spools complete	1,800	
Bedplate, bearings, &c.	6,300	
Brush rigging	450	
Other parts	1,000	
Magnet and field		20,710
Complete weight rotary converter		30,360

Tabulated Calculations and Specifications for a 900-Kilowatt Three-Phase Rotary Converter

The machine is illustrated in Figs. 396 to 398, pages 357 and 358; curves of its performance are given in Figs. 399 to 402 on page 359.

Description

Number of poles	12
Kilowatt output	900
Speed, revolutions per minute	250
Terminal volts, full load	500
„ „ no load	500
Amperes, output	1800
Frequency, cycles per second	25

Dimensions

Armature:

Diameter over all	84 in.
Length over conductors	27 „
Diameter of core at periphery	84 „
„ „ bottom of slots	$81\frac{1}{2}$ „
„ „ „ laminations	62 „
Length of core over laminations	12.5 „
Number of ventilating ducts	3
Width, each	$\frac{1}{2}$ „
Effective length, magnetic iron	9.9 „
„ „ of core ÷ total length	0.79
Length round periphery	264 in.
Pitch at surface	22 „
Insulation between sheets	10 per cent.
Thickness of sheets	0.016 in.
Depth of slot	1.25 „
Width of slot at root	0.44 „
„ „ surface	0.44 „
Number of slots	288
Gross radial depth of laminations	11 in.
Radial depth below teeth	9.75 „
Width of tooth at root	0.449 „
„ „ armature face	0.475 „
Size of conductor	0.125 in. by 0.400 in.

Magnet Core:

Length of pole-piece along shaft	12 in.
„ pole-arc, average	$15\frac{7}{8}$ „

Pole-piece and core consists of sheet-iron punchings 0.04 in. thick, japanned on one side, and built up to a depth of 12 in. The edges of pole-face are chamfered back 3 in. by $\frac{5}{16}$ in., and a copper bridge 14 in. by $\frac{1}{8}$ in., extending $1\frac{3}{8}$ in. under pole-tips, is inserted between poles to prevent "surging."

Pole arc ÷ pitch	0.722
Length of core radial	$9\frac{15}{16}$ in.
Size of magnet core (laminations)...	12 in. by 12 in.
Bore of field	$84\frac{3}{8}$ in.
Clearance (magnetic gap)	$\frac{3}{16}$ „

Spool:

Length	$8\frac{7}{16}$ in.
„ of shunt-winding space	4.9 „
„ „ series-winding space	3.5 „
Depth of winding space	$2\frac{3}{4}$ „

Yoke:

Outside diameter	123 in. & 114 in.
Inside diameter	105 in.
Thickness	$4\frac{1}{2}$ „
Length along armature	22

Beyond the 22-in. length along armature, projects on one side a ring $1\frac{1}{4}$ in. wide, which is grooved to receive the brush rocking gear.

Commutator:

Diameter	54 in.
Number of segments	576
„ „ per slot	2
Width of „ at surface	0.24
„ „ at root	0.215
Total depth of segment	$2\frac{1}{2}$ in.
„ length of segment	$17\frac{1}{2}$ „
Available length of segment	14 „
Width of insulation between segments	0.05 „

Collector:

Diameter	24 in.
Number of rings	3
Width of each ring	$3\frac{1}{2}$ in.
„ between rings	$1\frac{1}{2}$ „
Length over all	$18\frac{1}{2}$ „

Brushes:	Continuous Current.	Alternating Current.
Number of sets	12	3
Number in one set	8	8
Radial length of brush	2 in.	—
Width of brush	$1\frac{1}{4}$ „	$1\frac{1}{4}$ in.
Thickness of brush	$\frac{3}{4}$ „	6 „
Dimensions of bearing surface (one brush) ...	1.25 in. by 0.87 in.	1.25 in. by 1.1 in.
Area of contact (one brush)	1.08 square inch	1.35 square inch
Type of brush	Radial carbon	Copper

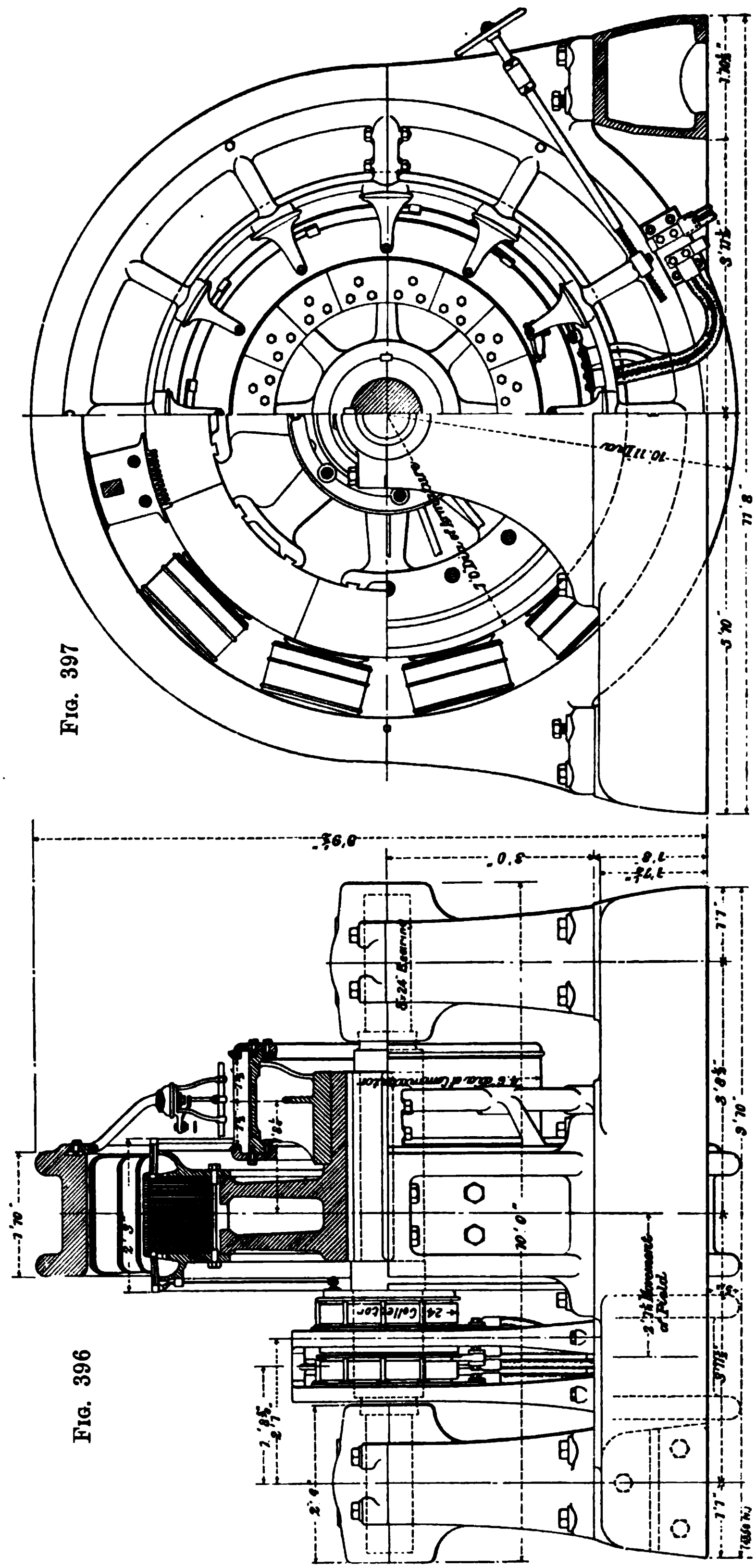


Fig. 397

Fig. 396

Figs. 396 and 397. 900-Kilowatt Three-Phase, Rotary Converter

TECHNICAL DATA.—ELECTRICAL

Armature:

Terminal volts, full load	500
Total internal volts	513
Number of circuits	12
Style of winding	Multiple-circuit drum
Times re-entrant	1
Total parallel paths through armature	12
Conductors in series between brushes	96
Type construction of winding	Bar

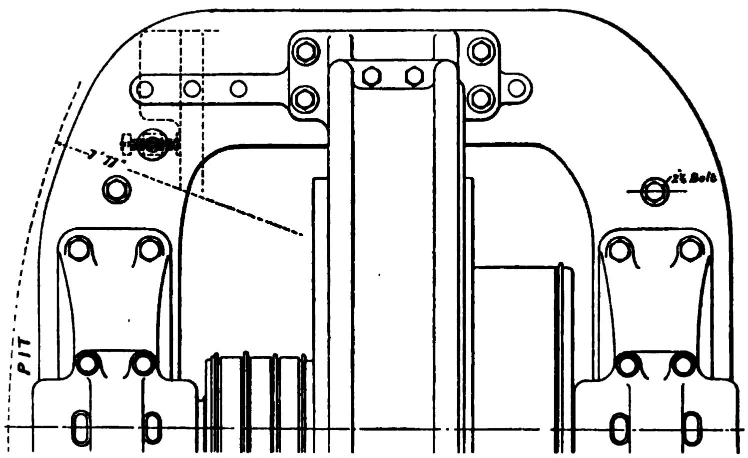
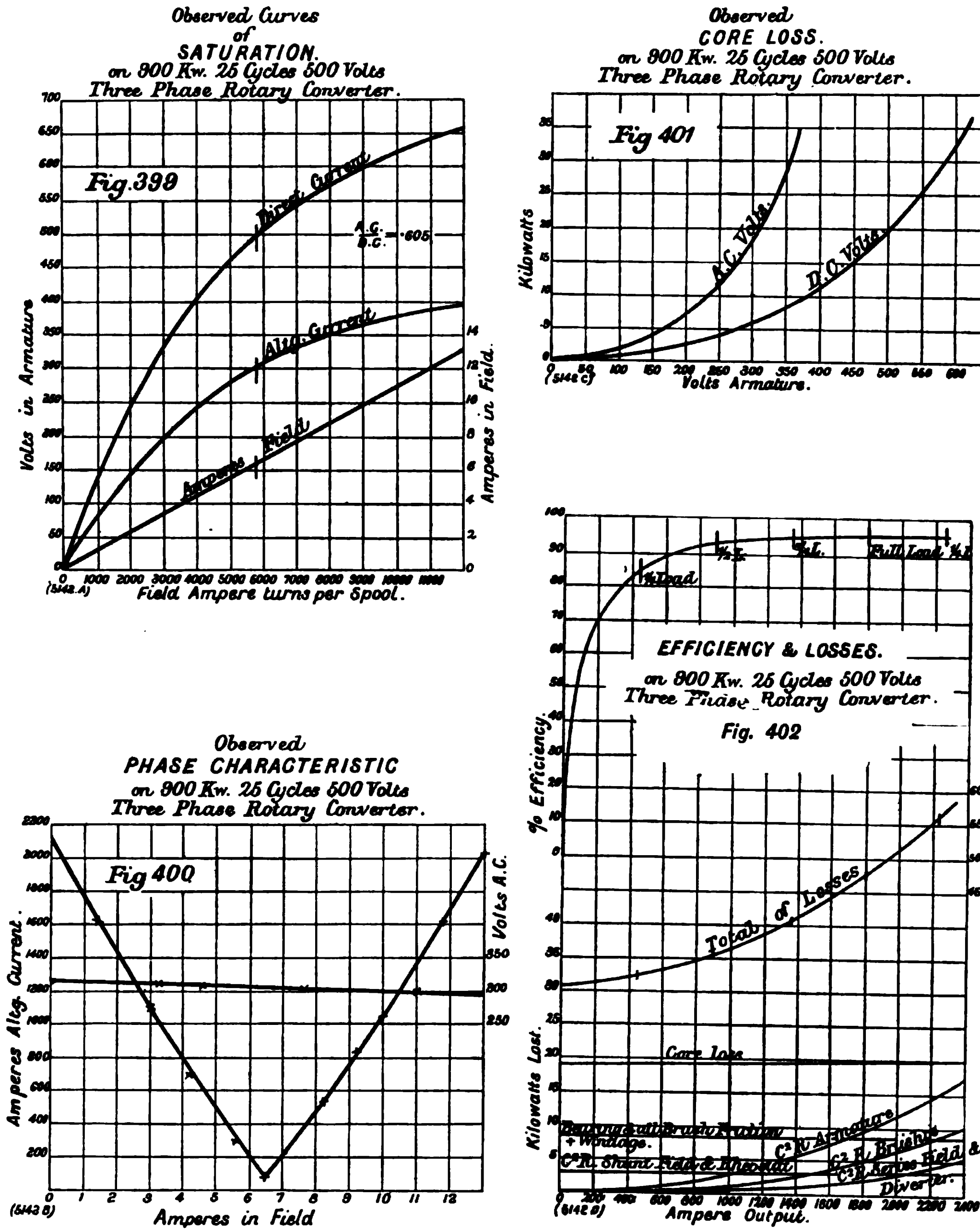


FIG. 398. 900-KILOWATT, THREE-PHASE, ROTARY CONVERTER

Number of face conductors	1152
„ slots	288
„ conductors per slot	4
Arrangement of conductors in slot	2 by 2
Number in parallel making up one conductor	1
Mean length of one armature turn	78 in.
Total number of turns	576
Turns in series between brushes	48
Length of conductor between brushes	3744 in.
Cross-section, one conductor	0.05 square inch
„ 12 conductors in parallel	0.60 „
Ohms per inch cube at 20 deg. Cent.	0.00000068
Per cent. increase in resistance 20 deg. Cent. to 60 deg. Cent.	16 per cent.
Resistance between brushes 20 deg. Cent.	0.00425
„ „ „ 60 „	0.00493

Assuming the current in three-phase rotary converter armature to be about three-fourths of that for continuous-current generator of same output, and a power factor of not quite unity, we may take current in armature conductor as $1800 \times 0.8 = 1440$ amperes.



Figs. 399 to 402. Curves of 900-Kilowatt, Three-Phase Rotary Converter

C R drop in armature at 60 deg. Cent.	7.1 volts
,, series coils	1 6 ,,
,, at brush contact surfaces	2.1 ,,
,, not allowed for in above	1.5 volts for cables and connections; figured on component currents
Amperes per square inch conductor (armature)	2400
,, ,, ,, brush-bearing surface	34.5
,, ,, ,, shunt windings	970
,, ,, ,, series windings	970

Space Factor:

Sectional area of slot = 1.25 × 0.44 = 0.55 square inch.

,, ,, copper in slot = 4 × 0.125 × 0.4 = 0.2 square inch.

"Space factor" = .2 ÷ 0.55 = 0.364, or 36.4 per cent. of total space is occupied by copper, leaving 63.6 per cent. for the necessary insulation.

Commutation:

Volts between segments, average...	10.4
Armature turns per pole	48

Resultant current per conductor $= \dfrac{1800 \times 0.8}{12} = 120$ amperes.

Resultant armature strength = 120 × 48 = 5800 armature ampere turns per pole

DETERMINATION OF REACTANCE VOLTAGE OF COIL UNDER COMMUTATION

Diameter of commutator	54 in.
Circumference of commutator	170 ,,
Revolutions per second	4.2
Peripheral speed, inches per second	708
Width of brush surface across segments	0.87 in.
Time of one complete reversal, seconds	0.00123
Frequency of commutation, cycles per second	407
Coils, short-circuited together per brush	3
Turns per coil...	1
Turns short-circuited together per brush	3
Conductors per group commutated together	6
Flux per ampere turn per inch gross length armature lamination	20
Flux through six turns carrying one ampere	1500
Inductance one coil of one turn	0.000015 henrys
Reactance of one coil of one turn	0.039 ohms
Current in one coil, amperes	150 (continuous-current component)
Reactance voltage one coil	5.8 volts

BINDING WIRE

Length of conductor between brushes	3774 in.
Cross-section of conductor between brushes	0.6 square inch
Weight of armature copper	3744 × 0.6 × 0.32 = 721 lb.
Centrifugal force	= 0.0000142 D N^2 lb.

Therefore, $0.0000142 \times 84 \times 250^2 = 74.7$ lb. exerted as centrifugal force by every pound of copper conductor on armature, and as there are 721 lb. weight of copper conductors, the total centrifugal force $= 721 \times 74.7 = 54{,}000$ lb.

Part of the centrifugal force is resisted by strips of hard wood driven into dovetail grooves running parallel to the length of the shaft at the tops of the slots, while the end projections and connections are held in place by 84 strands of No. 11 B. and S. phosphor-bronze wire arranged over both ends, in bands of six strands each, seven of these bands being employed for each end.

MAGNETIC CIRCUIT CALCULATIONS

Megalines *from* one pole at full load and 500 terminal volts (512.5 internal volts)	10.4
Assumed coefficient of magnetic leakage	1.20
Megalines *in* one pole at full load	12.5

The magnetic reluctance and the *observed* total number of ampere turns per field spool required were probably distributed approximately as follows :

Armature :

Core section	9.9 × 9.75 × 2 = 194 square inches
Length of magnetic circuit	11 in.
Density (kilolines)	54
Ampere turns per inch	16
Ampere turns	180

Teeth :

Number transmitting flux per pole-piece	17
Section at face	76 square inches
,, roots	80 ,,
Mean section	78 ,,
Length	1.25 in.
Apparent density (kilolines)	134
Width of tooth (mean) "*a*"	0.462 in.
,, slot "*b*"	0.44 ,,
Ratio of $a \div b$	1.05
Corrected density (kilolines)	128
Ampere turns per inch	1160
Ampere turns	1460

Gap:

Section at pole-face	190
Length	0.1875
Density at pole-face (kilolines)	54.5

Ampere turns = $.313 \times 54{,}200 \times 0.1875 = 3200$

Magnet Core:

Section (effective)	135 square inches
Length	$9\frac{15}{16}$ in.
Density (kilolines)	95
Ampere turns per inch	53
Ampere turns...	530

Yoke:

Section magnetic $2 \times 136 = 272$ square inches.

Length per pole	14.5 in.
Density (kilolines)	48
Ampere turns per inch	29
Ampere turns...	430

Summary of Ampere Turns

Armature core	180
„ teeth	1460
Gap	3200
Magnet core	530
Yoke	430
	5800

Spool Windings

Ampere turns per shunt spool, full load	5800
Watts per spool at 60 deg. Cent.	405
„ shunt winding at 20 deg. Cent.	200
„ series „ „ „	143
„ shunt „ 60 deg. Cent.	240
Shunt copper per spool	110 lb.
Volts at terminals of spool at 20 deg. Cent.	36
Amperes per shunt spool	6.3
Resistance at 20 deg. Cent. per spool, ohms	5.7
Turns per shunt spool	912
Total length of shunt conductor	4400 ft.
Pounds per 1000 ft.	24.9
Size of conductor	...No. 11 B. and S. gauge
Dimensions bare	...0.907 in. in diameter
„ double cotton covered	...0.101 „ „
Cross-section	...0.00647 square inch
Current density, amperes per square inch	970
Available winding space	4 in.
Number of layers	23
Turns per layer	40

Series:

Ampere turns, full load...	**3630**
Full-load amperes	**1800**
Amperes diverted	**350**
„ in series spools	**1450**
Turns per spool	**$2\frac{1}{2}$**
Size of conductor used	**2.5 in. by 0.075 in.**
Number in parallel	**8**
Total cross-section	**1.5 square inch**
Current density, amperes per square inch	**970**
Mean length of one turn	**4.83 ft.**
Total length, all turns on 12 spools	**150 ft. = 1800 in.**
Resistance of 12 spools at 20 deg. Cent.	**0.000816 ohm**
Series C^2R watts, total at 20 deg. Cent.	**1718**
„ „ per spool	**143**
„ „ „ at 60 deg. Cent.	**165**
Total weight of series copper, pound	**864**

Calculation of Losses and Heating

Armature:

Resistance between brushes, ohms	**0.00493 at 60 deg. Cent.**
C^2R loss at 60 deg. Cent.	**9700**
Frequency, cycles per sec. = C =	**25**
Weight of armature teeth	**500 lb.**
„ „ core	**6500 „**
Total weight of laminations	**7000 „**
Flux density in teeth, kilolines	**128**
„ „ core = D =	**54**
C.D. ÷ 1000 ...	**1.36**
Observed core loss per pound, watts	**2.8**
$K = \dfrac{\text{watts core loss per pound}}{(\text{C.D.} \div 1000)} =$	**2.05**
Total core loss...	**19,850**
„ armature losses	**29,550**
Armature diameter	**84 in.**
„ length	**27 „**
Peripheral radiating surface	**7150 square inches**
„ speed, feet per minute...	**5500**
Watts per square inch radiating surface	**4.1**

Commutator Losses and Heating

Commutator:

Area of all positive brushes	**51 square inches**
Amperes per square inch contact surface	**35**
Ohms „ „ assumed	**0.03**

Brush resistance, positive and negative	0.00116 ohm
Drop at brush contacts...	2.1 volts
C^2R loss at brush contacts	3700 watts
Brush pressure, pounds per square inch	1.15
„ „ total	117 lb.
Coefficient of friction	0.3
Peripheral speed, feet per minute	3550
Brush friction, foot-pounds per minute	124,000
„ „ watts	2800
Stray watts lost in commutator, assumed	600
Total „ „ „	7100
Diameter of commutator	54 in.
Available length of commutator	14 „
Radiating surface	2400 square inches
Watts per square inch of radiating surface...	2.9
Assumed rise of temperature per watt per square inch, after 10 hours' run	15 deg. Cent.
Total rise estimated on above basis	43 „

Collector Losses and Heating

Total contact area of all brushes	33.5 square inches
Amperes per square inch of contact surface	150
Ohms per square inch of contact (assumed)	0.003
Total resistance of brushes per ring	0.00027
Volts drop at brush contacts	0.48
C^2R loss at brush contacts per ring	850
„ „ „ in three rings	1,700
Brush pressure, pounds per square inch	1.6
„ „ total pounds	54
Coefficient of friction	0.3
Peripheral speed, feet per minute	1,580
Brush friction, pounds per minute	25,500
„ „ watts lost	600
Total watts lost in collector	2,300
Diameter collector	24 in.
Effective length radiating surface	11 „
Total radiating surface	820 square inches
Watts per square inch radiating surface	2.8
Assumed rise of temperature per watt per square inch, after 10 hours' run	15 deg. Cent.
Total rise estimated on above basis	42 „

Field Spool Losses:

Spool C^2R loss at 60 deg. Cent. per shunt coil	240
C^2R loss at 60 deg. Cent. per series coil	165
Total loss per spool, watts	405
„ in 12 spools, watts	4850

Efficiency

Full load, watts output	900,000
Core loss	19,850
Commutator losses	7,100
Collector losses	2,300
Armature C^2R loss at 60 deg. Cent.	9,700
Shunt spools C^2R loss at 60 deg. Cent.	2,900
,, rheostat C^2R loss at 60 deg. Cent.	300
Series spools C^2R loss at 60 deg. Cent.	1,700
,, diverter C^2R loss at 60 deg. Cent.	500
Friction, bearings and windage	5,100
Total input	949,450

Commercial Efficiency:

Full load	95 per cent.

Materials:

Armature core	Sheet steel
,, spider	Cast iron
,, conductors	Copper
Commutator segments	,,
,, leads	Stranded copper
,, spider	Cast iron
Pole-piece	Laminated sheet iron
Yoke	Cast steel
Magnet core	Laminated sheet iron
Brushes	Carbon
Brush-holder	Brass
,, yoke	Gun-metal
Binding wire	Phosphor-bronze
Insulation, commutator	Mica

Weights

Armature:

	Lb.
Laminations	7,000
Copper	720
Spider	3,000
Shaft	3,000
Flanges	800

Commutator:

Segments	2,100
Mica	130
Spider	1,650
Press rings	280
Sundry other parts	350
Collector rings, complete	1,070
Armature, commutator, collector, and shaft complete	20,100

Brought forward		20,100
Magnet:		
Yoke		13,000
Poles		6,000
Field:		
Shunt coils, copper	1,320	
Series „ „	860	
Total copper	2,180	
Spools complete, including flanges and all insulation... ...		5,600
Bedplate, bearings, &c.		18,000
Brush gear		1,200
Sundry other parts		2,200
Total weight of rotary converter		66,100

The Starting of Rotary Converters

The starting and synchronising of rotary converters may be accomplished in any one of several ways. The simplest, at first sight, is to throw the alternating-current terminals of the rotary converter directly on the alternating-current mains: but this, although often practicable, has several disadvantages. By this method, the current rush at the moment of starting is generally in excess of the full-load current input to the rotary converter; and as it lags in phase by a large angle, it causes a serious drop of line voltage and affects the normal line conditions, to the serious detriment of other apparatus on the line. This large current gradually decreases as the speed of the rotary converter increases. The action of the rotary converter in starting is analogous to that of an induction motor. The rotating magnetic field set up by the currents entering the armature windings induces—but very ineffectively—secondary currents in the pole-faces, and the mutual action between these secondary currents and the rotating field imparts torque to the armature, which revolves with constantly accelerating speed up to synchronism. Then the circuit of the rotary converter field spools is closed and adjusted to bring the current into phase. But when the armature is first starting, the field spools are interlinked with an alternating magnetic flux generated by the current in the armature windings, and, in normally-proportioned field spools, with several hundreds or thousands of turns per spool, a dangerously high secondary voltage is generated in these spools. Hence they must be insulated better than field spools ordinarily are, not only between layers, but between adjacent turns; and wire with double or triple cotton covering should be used. However, the most frequently-occurring breakdown due to this cause is from winding to frame, hence extra insulation should be used between these parts.

The terminals of the different field spools should be connected up to a suitable switch, arranged so that the field winding may be conveniently broken up into several sections; otherwise, if a thousand volts or so are induced in each spool, the strain on the insulation between the ends of these spools in series and the frame is severe.

At starting, this switch must always be open; it must not be closed until the armature has run up to synchronous speed, which is observed by the line current falling to a much smaller value. This special switch is then closed, afterwards the main field switch is closed also; whereupon a still further decrease in the line-current occurs, due to improved phase relations, and the process of synchronising is completed.

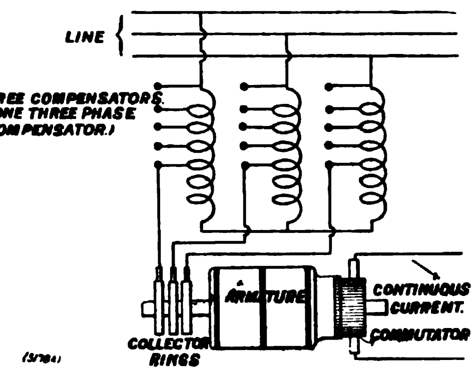


FIG. 403. CONNECTIONS FOR A THREE-PHASE ROTARY, WITH COMPENSATOR

By means of a compensator, this heavy current on the line at starting may be dispensed with. The connections for a three-phase rotary, with compensator, are as shown in the diagram of Fig. 403.

At the instant of starting the collector rings are connected to the three lowest contacts, hence they receive but a small fraction of the line voltage, and would receive several times the line current; *i.e*, if the taps into the compensator winding are, say, one-fifth of the way from common connection to line, then the rotary converter has one-fifth the line voltage and five times the line current. As the converter runs up in speed, the terminals are moved along until, at synchronism, the collector is directly on the line.

Another difficulty encountered when the rotary converter is started from the alternating-current end, is the indeterminate polarity at the commutator when the rotary is made to furnish its own excitation. Unless some independent source of continuous current is available at

the rotary converter substation, the rotary is dependent for its excitation upon the polarity that its commutator happens to have at the instant of attaining synchronism. If there are two rotary converters at the substation, and the first comes up with the wrong polarity, then it may be allowed to run so, temporarily, till the second one is synchronised. The second one can be given either polarity desired, by using the first as an independent source of continuous current. Then from the second one, the polarity of the first may be reversed into the correct direction, and the second rotary converter shut down. Obviously, however, this indeterminateness of the initial polarity constitutes a further inconvenience and objection to starting rotary converters, by throwing them directly on to the alternating-current line. But in the case of large capacity, slow-speed rotary converters, containing therefore heavy armatures, it has been found practicable to control the polarity of the first machine when it is started up from the alternating current side. One must stand ready by the field switch as the machine approaches synchronism, when the pointer of the continuous-current voltmeter will commence to vibrate rapidly with short swings about the zero mark. These will finally be followed by a couple of fairly slow, indecisive, long swings, in opposite directions from the zero mark. Near the maximum point of whichever of these swings is in the direction of the desired polarity, the field switch should be closed, and the machine will excite itself, provided the field terminals are correctly positive and negative. Otherwise—which might happen on the first run, or after alterations—the field terminals will require to be reversed.

The required line current is greatly reduced by starting generator and rotary converter up simultaneously. The latter is then, from the instant of starting, always in synchronism with its generator, and the conditions of running are arrived at with a minimum strain to the system. But the conditions of routine operation rarely render this plan practicable.

A method sometimes used is to have a small induction motor direct-coupled to the shaft of the rotary converter, for the purpose of starting the latter with small line currents. This, however, is an extra expense, and results in an unsightly combination set.

Where there are several rotary converters in a substation, a much better way is that described in a recent British patent specification, in which the station is provided with a small auxiliary set, consisting of an

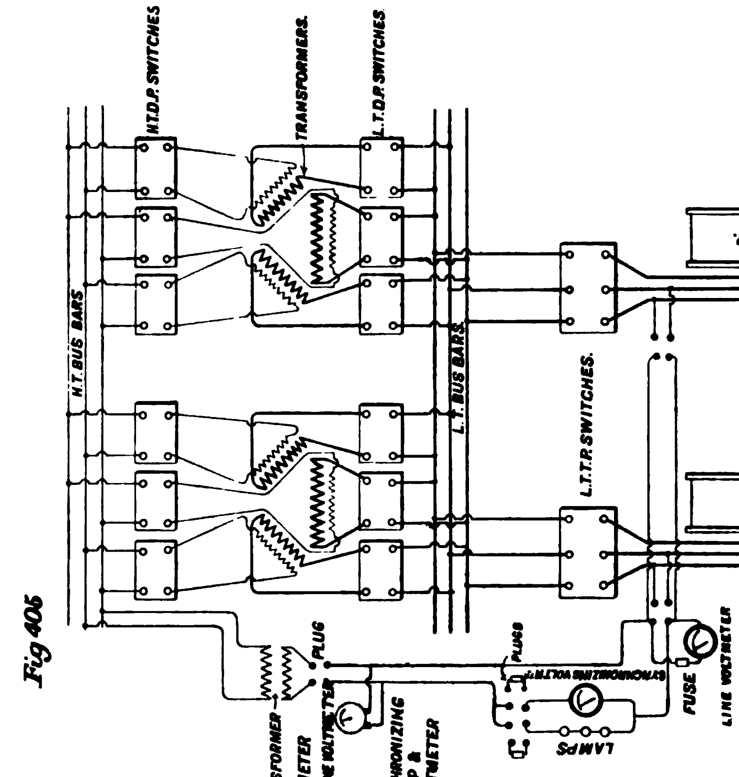


FIG. 405. DIAGRAM OF CONNECTIONS APPLICABLE TO THREE-PHASE ROTARIES

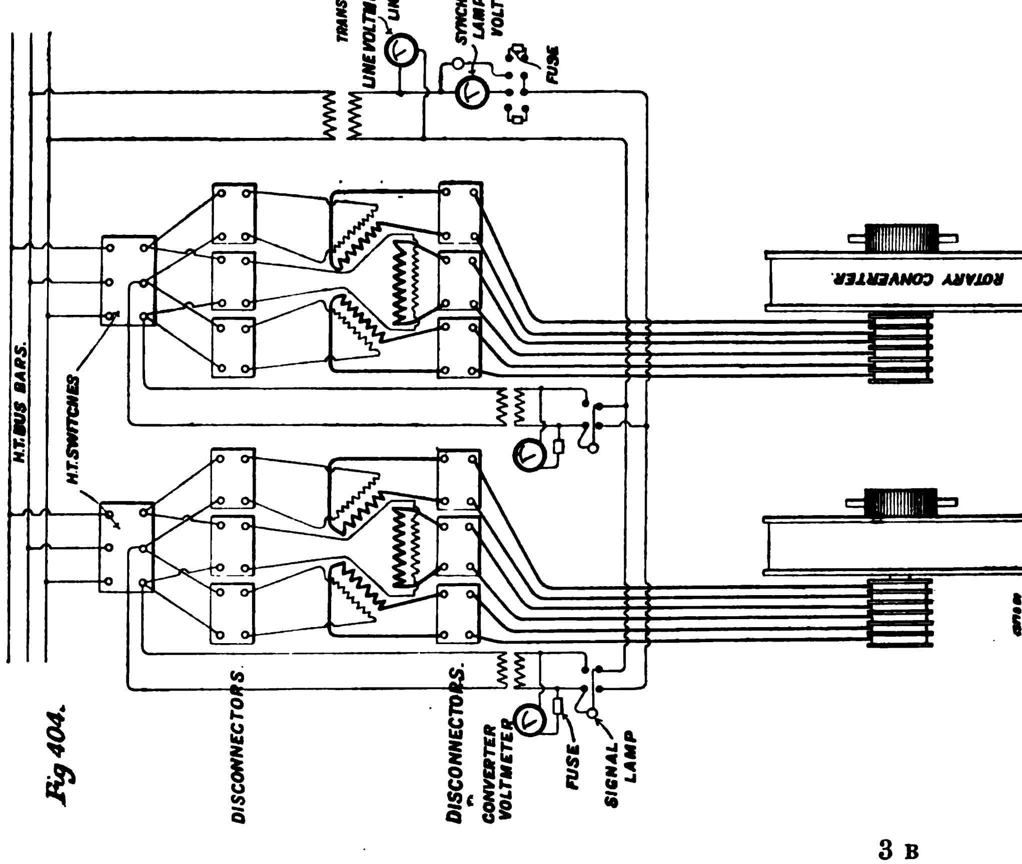


FIG. 404. DIAGRAM OF CONNECTIONS APPLICABLE TO SIX-PHASE ROTARIES

induction motor direct-coupled to a continuous-current dynamo, the latter being only of sufficient capacity to run the rotary converters one at a time up to synchronous speed as continuous-current motors. When this speed is arrived at, and synchronism attained, between the alternating-current collector rings and the line, the switch between them is closed, and the rotary converter runs on from the alternating-current supply.

In many cases a continuous-current system derives its supply partly from continuous-current generators and partly from rotary converters. In

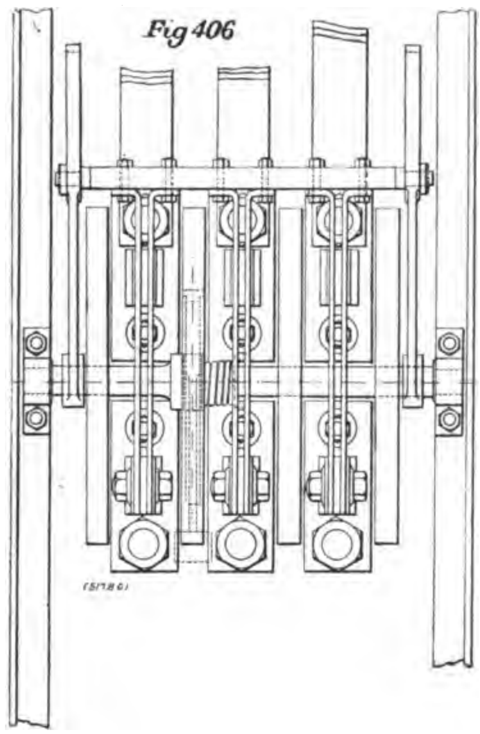


FIG. 406. QUICK-BREAK SWITCH

such cases the rotary converter is simply started up as a motor from the continuous-current line, and then synchronised.

On the Continent it is very customary to operate storage batteries in the substations, in parallel with the rotary converters; the batteries being charged by the rotaries during times of light load, and helping out the rotaries with heavy loads. They are known as "buffer batteries," and are of considerable assistance in maintaining uniform voltage and more uniform load on the generating plant. Moreover, they render the substation independent of the rest of the system for starting up the rotary converters.

SYNCHRONISING ROTARY CONVERTERS

One has the choice of synchronising the rotary converter, either by a switch between the collector rings and the low potential side of the step-down transformers, or of considering the step-down transformers and the rotary converter to constitute one system, transforming from low-voltage continuous current to high-voltage alternating current, and synchronising by a switch placed between the high-tension terminals of the transformers and the high-tension transmission line. This latter plan

Fig 407

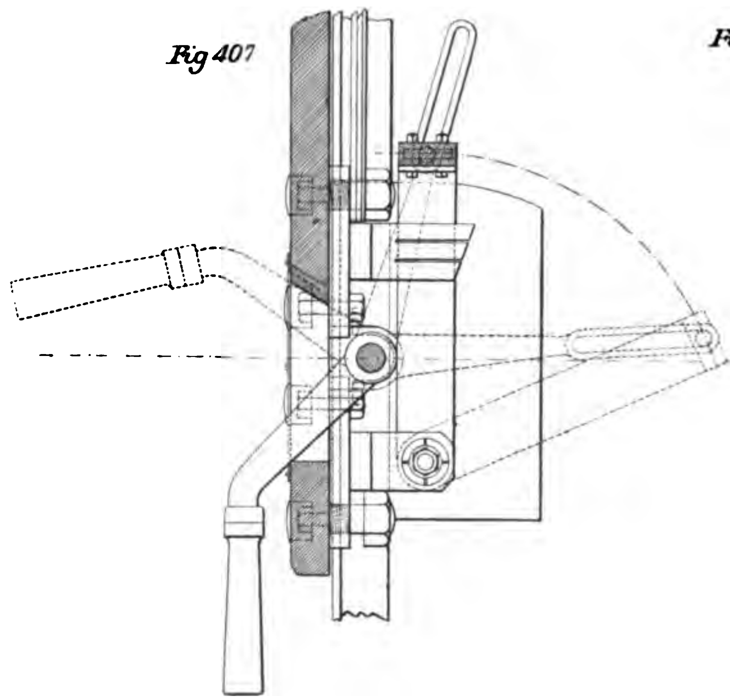
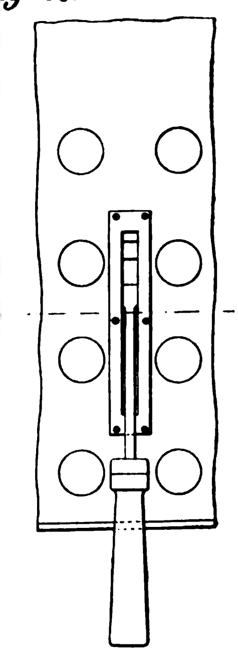


Fig 408.



FIGS. 407 AND 408. QUICK-BREAK SWITCH

is, perhaps, generally the best; as for the former plan, one requires a switch for rather heavy currents at a potential of often from 300 to 400 volts; and such a switch, to be safely opened, is of much more expensive construction than a high-tension switch for the smaller current. Moreover, for six-phase rotaries, the low-tension switch should preferably have six blades, as against three for the high-tension switch. It is much simpler, in six-phase rotary converters, to have an arrangement which obviates opening the connections between the low-tension terminals of the transformers and the collector ring terminals; although in such cases

some type of connectors should be provided which may be readily removed when the circuits are not alive, for purposes of testing.

The arrangement shown in Fig. 404, on page 369, represents a plan for synchronising and switching, on the high-tension circuits, and adapted to six-phase rotaries.

Fig. 405, on same page, shows diagrammatically a plan for a three-phase system where the switching is done on the low-tension circuits. The quick-break switch used, which is necessarily of rather elaborate construction, is illustrated in Figs. 406 to 408, pages 370 and 371. This switch was designed by Mr. Samuelson. The switch is designed for the breaks to occur on the back of the board, thus protecting the operator.

Voltage Ratio in Rotary Converter Systems

As already shown, there is a tolerably definite ratio between the alternating-current voltage at the collector rings and the continuous-current voltage at the commutator. This lack of flexibility is to a certain degree a source of inconvenience; hence, methods whereby it may be avoided possess interest. A rotary converter with adjustable commutator voltage is desirable for the same purposes as an over-compounded generator, and also for charging storage batteries.

If the generators, transmission line, transformers and rotary converters possess sufficient inductance, the commutator voltage may be varied within certain limits, by variations of the field excitation of converter or generator, or both. By weakening the generator excitation or strengthening the rotary excitation, the line current may be made to lead, and a leading current through an inductive circuit causes an increased voltage at the distant end of the line. Hence, by suitable adjustment of the excitation, the voltage at the collector rings of the rotary, and consequently also its commutator voltage, may be increased. Strengthening the generator field or weakening the converter field, or both, causes the current to lag, and results in a decreased commutator voltage. These effects may be intensified by placing inductance coils in series in the circuits.

Another method of controlling the commutator voltage is by equipping the step-down transformers with switches, whereby the number of turns in primary or secondary, and hence the ratio of transformation, may be adjusted. A much better method is that in which an induction

regulator is used between the transformer secondary terminals and the rotary converter. This consists of a structure like an induction motor. Series windings are put on the one element, say the stator, and potential

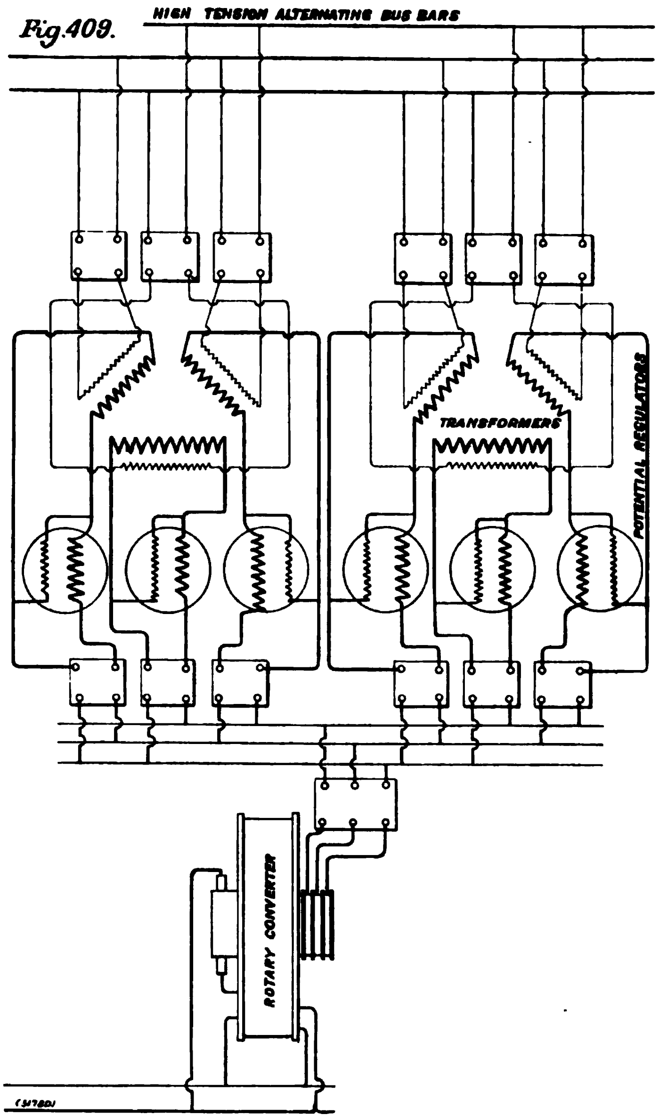


Fig. 409. Diagram of Connections for Converter Set

windings on the rotor. The rotor may be progressively advanced through a certain angle, and at each angular position will raise or lower the voltage at the collector rings by a certain amount, by virtue of the mutual action of the series and potential coils. The connections are shown diagrammatically in Fig. 409.

A small auxiliary rotary converter, having a voltage equal to the amount by which it is desired to increase or decrease the commutator voltage of the main rotary, and with a current capacity equal to that of the main rotary, may be employed with its commutator in series with that of the main rotary. The auxiliary rotary should have field coils capable of exerting a great range of excitation. Its collector should be supplied from a special transformer or transformers, with the primary and secondary coils considerably separated, so as to permit of much magnetic leakage between them. This gives large inductance to the small branch circuit

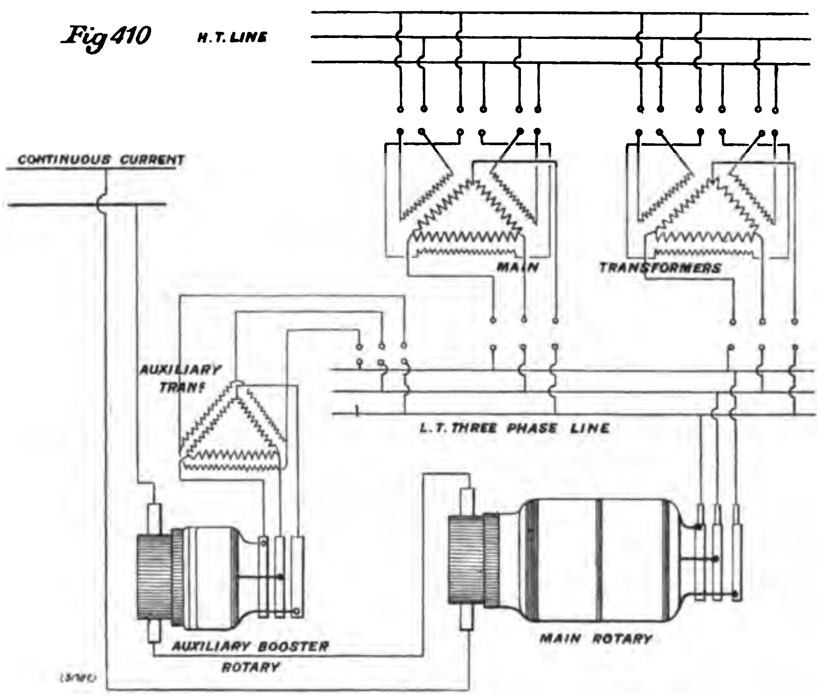


FIG. 410. DIAGRAM OF CONNECTIONS FOR CONVERTER SET

leading to the auxiliary rotary, and by regulation of its field excitation, a very wide range of voltage at its commutator is secured. It has the great advantage over inductance in the main circuit that it gives a wide range of voltage variation for the combined set, consisting of main and auxiliary rotary, without working at low power factors. This is obviously the case, since the main rotary may be adjusted to work at a power factor of unity, while it is only the relatively small amount of energy consumed by the small-capacity auxiliary rotary, which is supplied at a low power factor. The effect on the power factor of the main system, caused by the power factor of the small rotary, may be completely

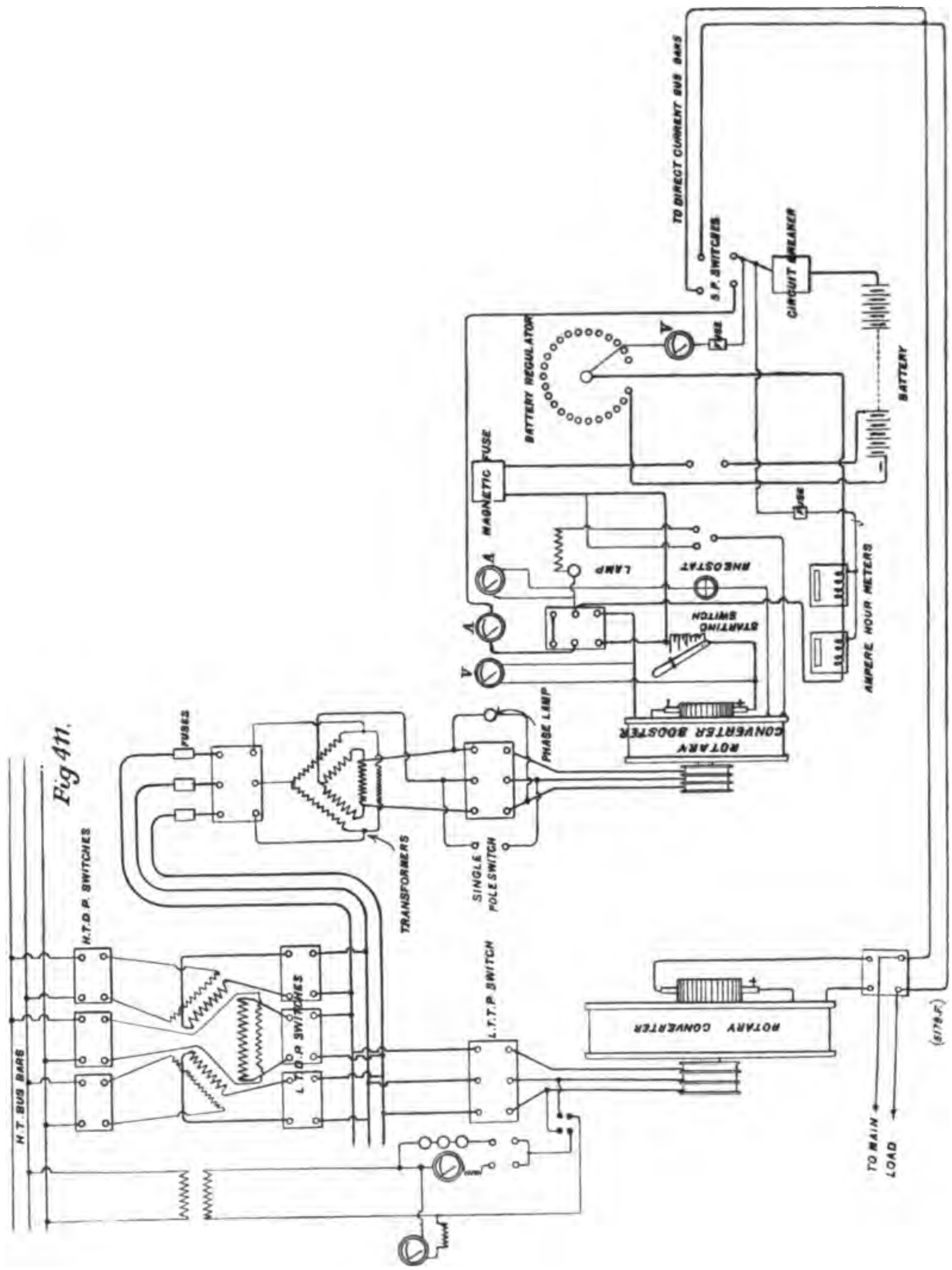
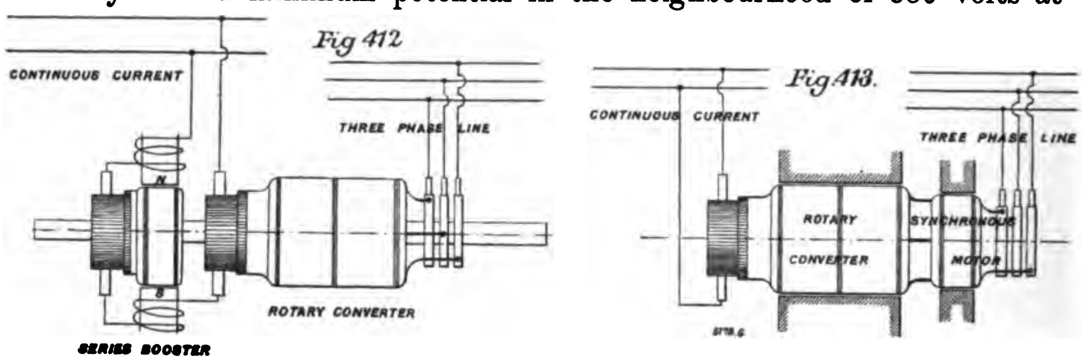


FIG. 411. DIAGRAM OF CONNECTIONS FOR CONVERTER SET

neutralised, and the resultant power factor restored to unity by the simple method of running the large main rotary with a slight over- or under-excitation, and hence with a power factor slightly lower than unity, to compensate for the lagging or leading current, as the case may be, consumed by the small auxiliary rotary converter. The scheme is illustrated diagrammatically in Fig. 410, page 374.

A similar kind of apparatus has been used for the express purpose of charging storage batteries from a 500-volt line. With maximum excitation, it supplied 200 volts more, giving the 700 volts required by the battery toward completion of the charge. This rotary converter had a shunt winding, and also a *negative* series coil; and when finally adjusted it had the interesting property of *automatically* charging the battery from a minimum potential in the neighbourhood of 530 volts at



FIGS. 412 AND 413. DIAGRAMS OF CONNECTIONS FOR CONVERTER SETS

the commencement of the charge, up to about 700 volts when fully charged. Moreover, the current, amounting to some 40 amperes at the commencement, gradually fell off to about 30 amperes when the battery was fully charged. That is, when the battery charge is low, and this rotary converter is thrown on in series with the 500-volt line, it automatically regulates its own excitation, so that, while giving 30 volts and 40 amperes at first, it finished up with 200 volts and 30 amperes. Its shunt coils are excited from its own commutator; hence at gradually increasing voltage.

Its series winding is connected to act in opposition to the shunt winding. This negative series winding was at first put on to protect the rotary from the effect of sudden variations of voltage on this 500-volt circuit. Thus, if the line voltage suddenly rose to 520 volts, the addition of the rotary voltage would have sent a much heavier current into the battery; a negative series winding tended to equalise the resultant

voltage in spite of line variations, and proved to contribute very markedly to the automatic regulation of current and voltage to the varying requirements during the process of charging the storage battery.

In Fig. 411, page 375, is given a diagram of its connections.

An alternative scheme to that of a small auxiliary rotary converter, and perhaps, on the whole, the best arrangement of all, consists in the addition of a small continuous-current machine on an extension of the shaft of the main rotary converter. If its fields are excited in series with the load, and its commutator connected in series with that of the main rotary converter, the combined set may be adjusted to over-compound to any desired extent. Fig. 412 gives a diagram of this scheme.

A great disadvantage of both these last schemes is that the commutator of the auxiliary machine carrying the main current must have substantially as great a radiating surface as the main commutator, and hence is expensive. The commutator losses are also doubled.

Still another interesting arrangement for giving an adjustable ratio of conversion of voltage is that illustrated in Fig. 413, wherein a small synchronous motor is directly connected on the shaft of the rotary, which requires no collector rings, those of the synchronous motor serving for the set. The synchronous motor has a separate field system, by varying the excitation of which the percentage of the voltage consumed in the sychronous motor is varied, and consequently also the total ratio of conversion. This scheme avoids the losses in an extra commutator, and is a very flexible method.

Running Conditions for Rotary Converters

The conditions relating to starting rotary converters have been considered on pages 366 to 370. After being finally brought to synchronous speed, there remain various adjustments requisite to secure the most efficient performance, and to adapt them to best fulfil the special requirements.

Phase Characteristic.—The term "phase characteristic" is generally applied to a curve plotted with field excitation (preferably expressed in ampere-turns per field spool), for abscissæ, and with amperes input per collector ring as ordinates. Such a curve has been given for no load in Fig. 400, on page 359, and from an examination of it, one learns that at normal voltage between collector rings (310 volts in the machine in question), and a field excitation of 6.4 amperes (5800 ampere-

turns per pole), there was required only about 80 amperes per phase to run the rotary converter unloaded. This is the condition of minimum current input; with weaker field excitation the current lags, and with stronger it leads, in both cases increasing rapidly in amount with the varying field excitation. The curve shows that with no field excitation, the current per phase increases to about 2100 amperes, and it also reaches approximately this same value with twice the normal field excitation.

If the current is in phase at the point of minimum current input, then the volt-amperes will be equal to the sum of the no-load losses.

No-Load Losses

		Watts.
Core and stray losses at normal voltage	=	20,000
Friction and collector C^2R losses	=	8,000
Shunt field self excitation = 6.4×500	=	3,200
Total no-load losses	=	31,200
Watts per phase	=	10,400
"Y" voltage = $\frac{310}{\sqrt{3}}$	=	180 volts.
Current per phase (*i.e.*, entering each collector ring) = $\frac{10,400}{180}$	=	58 amperes.
Hence we have an unaccounted-for balance of 80 − 58	=	22 amperes.

This is due partly to a difference in the wave forms of the generator and the rotary, but chiefly to so-called "surging" effects, and will be a varying value, depending upon the motive power driving the generating alternator, and upon the methods employed to limit the effect. It will be considered in a subsequent paragraph.

Neglecting the "surging" effect for a given field excitation, the power factor of the incoming current may be estimated. Thus the curve of Fig. 400 shows that with the excitation of 3.2 amperes (half the normal excitation) there is an incoming current of 1000 amperes per phase. One thousand amperes entering a collecting ring corresponds to $\frac{1000}{\sqrt{3}} = 580$ amperes in the armature conductor.

Resistance of armature between commutator brushes has been given as 0.005 ohm at 60 deg. Cent. = R. (See page 358.)

Then the resistance of one branch (*i.e.*, one side of the Δ) will be 1.33 R = 0.0067 ohm.[1]

In each branch there will be a C^2R loss of $580^2 \times 0.0067 = 2250$ watts, and therefore a total armature C^2R of $3 \times 2250 = 6750$ watts. The field excitation with regulating rheostat losses will be one-half its former value, *i.e.*, 1650 watts. The core loss and friction remain substantially as before, but the collector C^2R loss is increased by 500 watts.

SUMMARY

	Watts.
Armature C^2R ...	6,750
Field self-excitation	1,650
Core and stray losses	20,000
Friction and collector C^2R losses	8,500
Total of losses	36,900
Total per phase ...	12,300

Volt-amperes input phase = $580 \times 310 = 180{,}000$.

Hence power factor $= \dfrac{12.3}{180} = 0.068$.

---

[1] Proof that, if R = armature resistance between commutator brushes, then 1.33 R = resistance of one side of the Δ.

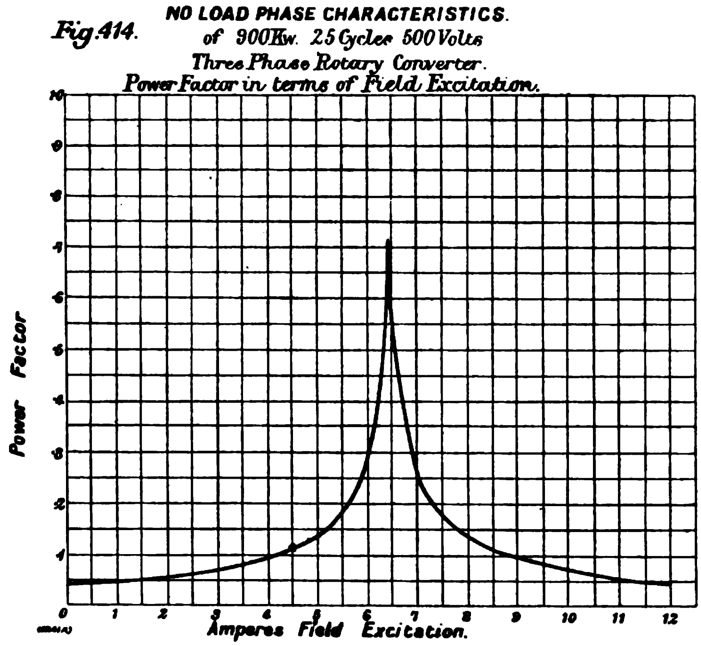
Take the case of the present rotary. It has 12 poles, and a multiple-circuit single winding. Therefore, there are 12 paths through the armature from the positive to the negative brushes. There are 576 total turns on the armature. Hence, each of the 12 paths has 48 turns. R = the resistance of the 12 paths in parallel. $\therefore$ 12 R = resistance of one path of 48 turns. But between two collector rings, the 576 total turns are divided into three groups of 192 turns each. One side of the Δ is made up of one such group arranged in six parallel paths of $\frac{192}{6} = 32$ turns each; 32 turns in series will have a resistance of

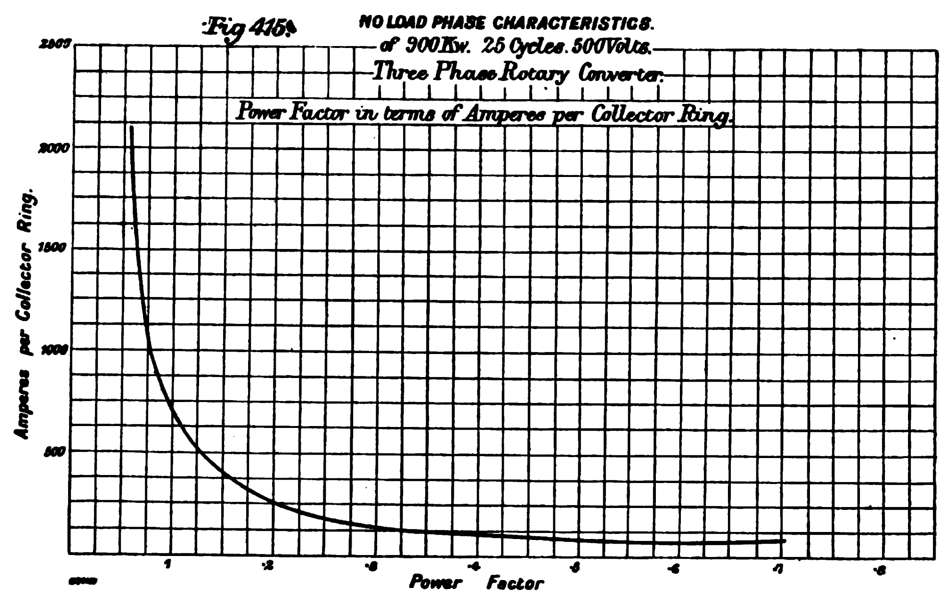
$$\frac{32}{48} \times 12\,R = 8\,R,$$

and six paths in parallel will have a resistance of $\frac{8\,R}{6} = 1.33$ R, and this equals the resistance of one side of the Δ. *Q.E.D.*

Any difficulties in understanding this subdivision of the winding into groups and parallel paths may be removed by a study of the winding diagram for the multiple-circuit single winding shown in Fig. 373, on page 323. Analogous investigations of two-circuit single windings, and of multiple windings of both the two-circuit and multiple-circuit type, will yield the same result, *i.e.*, that the resistance of one side of the Δ is equal to 1.33 R, for three-phase rotaries. For an examination of these latter cases, one may make use of the winding diagrams of Figs. 374 and 375, on pages 324 and 325.

Similar calculations for other values of the field excitation give data for plotting other phase characteristic curves for no load, that is, for no





FIGS. 414 AND 415. POWER FACTOR CURVES FOR A 900-KILOWATT ROTARY CONVERTER

output from the commutator. Thus in Fig. 414 the power factor is plotted in the terms of the field excitation ; and in Fig. 415 in terms of the amperes input of the collector ring. These curves have all corresponded to

no load, but other phase characteristic curves may be obtained for various conditions of load.

In Fig. 416 are given phase characteristic curves at no load, half load, and full load for a 125-kilowatt rotary converter. It will be observed that the phase characteristic curves with load possess the same general features as the curve for no load, though less accentuated.

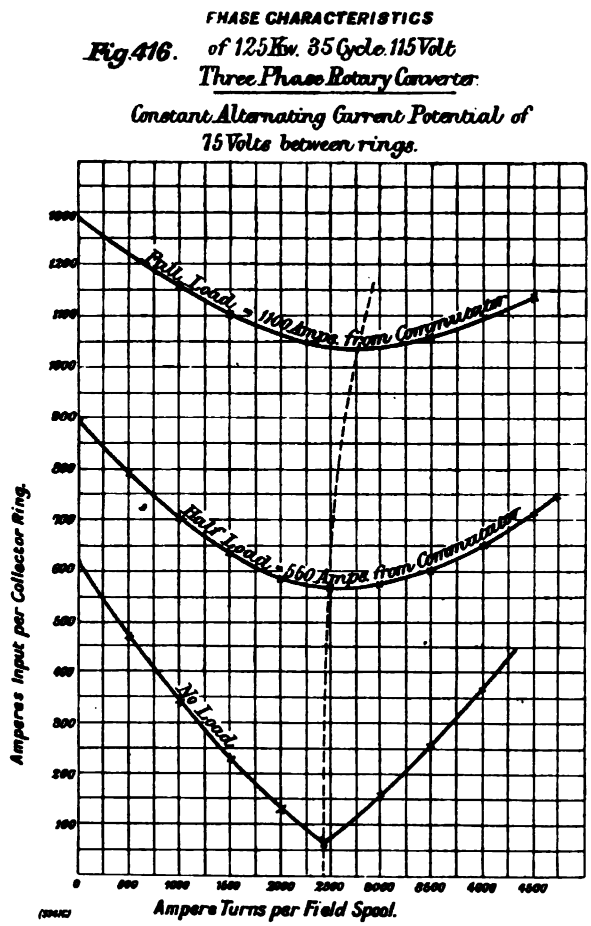


FIG. 416. CHARACTERISTIC CURVES FOR A 125-KILOWATT ROTARY CONVERTER

In Fig. 417, on page 382, these curves are transformed into three others, in which the power factors are plotted in terms of field excitation; and in Fig. 418 the power factors are plotted in terms of amperes input per collector ring.

Figs. 414, 416, and 417 show the importance, especially with light loads, of careful adjustment of the excitation. The power factor falls off very rapidly indeed with variations of the field excitation from

the normal value. However, with load the variations are comparatively moderate, and field regulation can then advantageously be employed as a means of phase control; and through the intermediation of line and armature inductances, sometimes aided by auxiliary inductances employed for the express purpose, a considerable working range of voltage at the commutator of the rotary converter may be obtained.

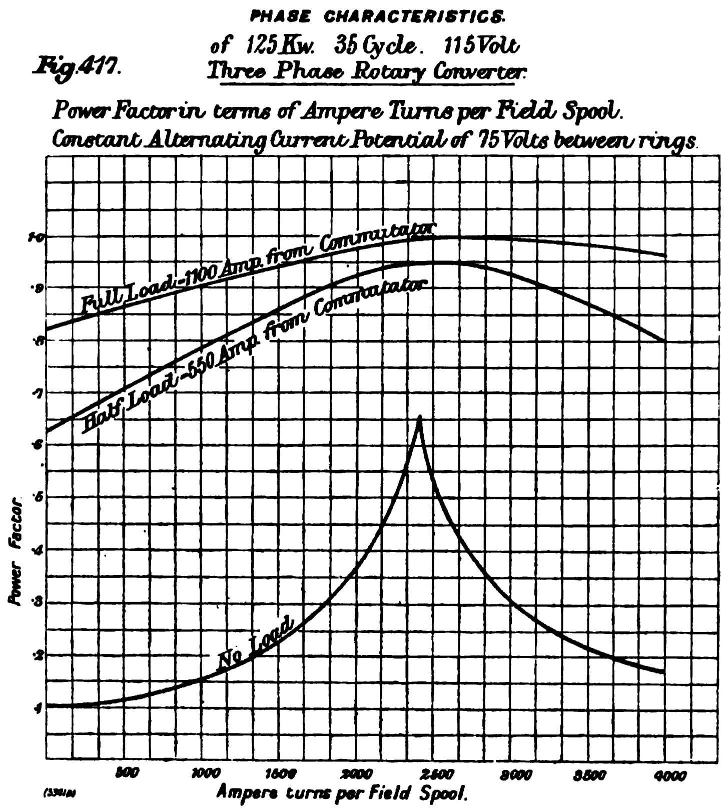


FIG. 417. CHARACTERISTIC CURVES FOR A 125-KILOWATT ROTARY CONVERTER

This brief description of the phase characteristic curves permits of now explaining in a rough, practical way, what causes the current to lag or lead with varying field excitation, and also what controls and determines the extent by which it shall lag or lead. Suppose a generator say by hand regulation of the field excitation, is made to furnish 310 volts under all conditions of load and phase, to the collector rings of a rotary converter. (Assuming the rotary converter to be of very small capacity relatively to that of the generator, these variations will not materially affect the generator voltage, which will remain approximately constant.)

It has been shown that there will be substantially 500 volts at the commutator when there are 310 volts between collector rings. This is fairly independent of the field excitation. But figuring from the 310 volts at the collector rings, or the 500 volts at the commutator, the result arrived at is that there is a magnetic flux M per pole-piece, linked with the armature winding turns. When the field excitation is such as to afford the requisite magnetomotive force for impelling this flux M against the reluctance of the magnetic circuit, there will be no current in the armature: or, rather, only the small amount necessary to supply the power repre-

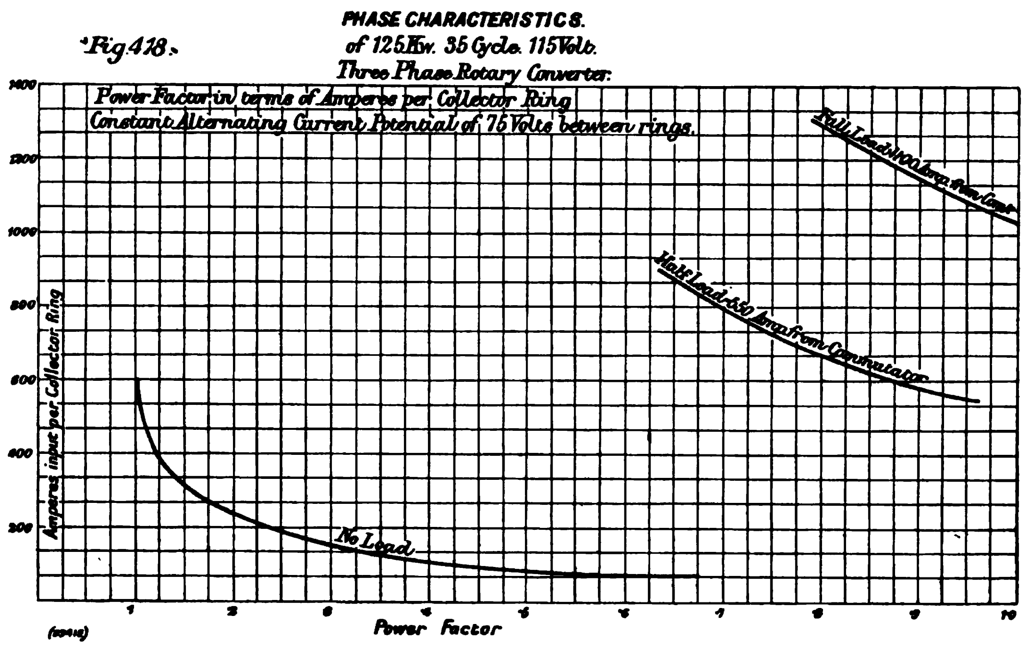


FIG. 418. CHARACTERISTIC CURVES FOR A 125-KILOWATT ROTARY CONVERTER

sented by the no-load losses. But if the field excitation is weakened, say, to one-half, then, since there is still the same terminal voltage, it follows that there must also be the same flux M impelled through the same magnetic circuit. The remaining part of the required magnetomotive force has, therefore, to be sought for elsewhere. It is, in fact, furnished by a lagging armature current, which then flows into the collector rings. This component does no work, hence it is 90 deg. out of phase. The resultant current is composed of the energy component which overcomes the losses, and this wattless current. Thus in the analysis on page 378 of the phase characteristic curve of Fig 400, it was found that reducing the field excitation from 6.4 amperes, (corresponding to unity power factor), to

3.2 amperes, increased the input from 80 amperes per collector ring to 1000 amperes per ring. The magnetising component of this 1000 amperes was $\sqrt{1000^2 - 80^2}$, and hence scarcely differed from 1000 amperes. There are, therefore, $\frac{1000}{\sqrt{3}} = 580$ amperes per side of the "delta," or $\frac{580}{6} = 97$ amperes per armature conductor. This, assuming a sine wave of incoming current, is $97 \times \sqrt{2} = 138$ maximum amperes. A current of 6.4 amperes in the field corresponded to a magnetomotive force of 5,800 ampere-turns.

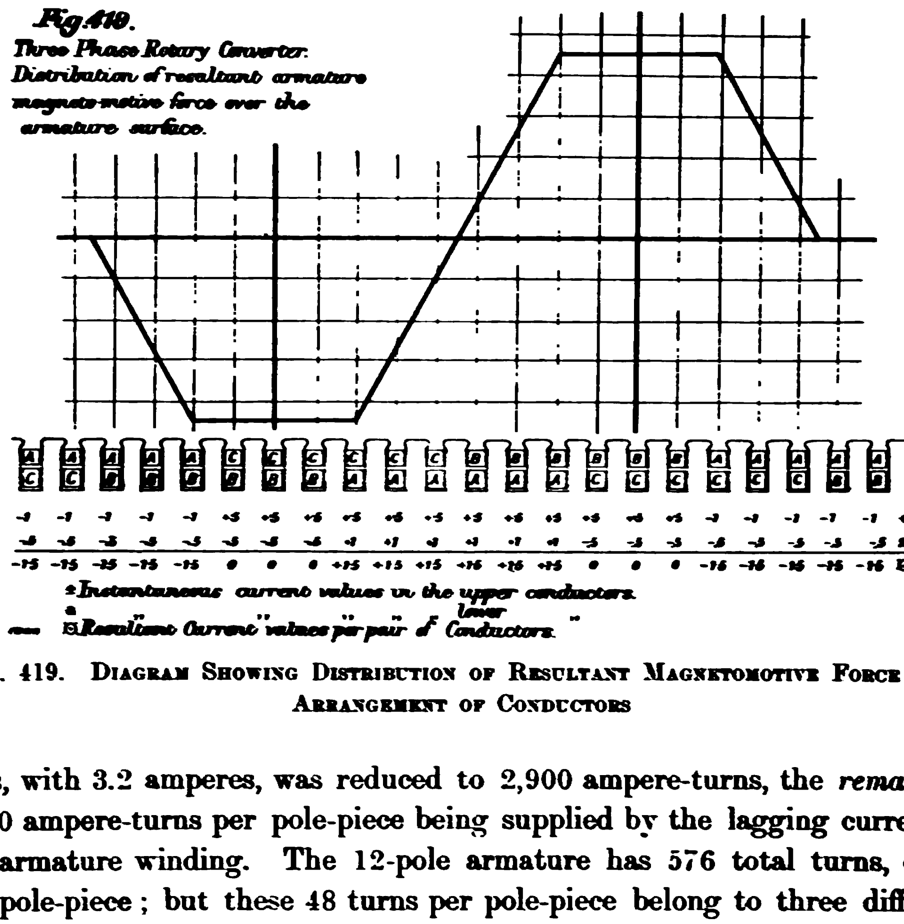


FIG. 419. DIAGRAM SHOWING DISTRIBUTION OF RESULTANT MAGNETOMOTIVE FORCE AND ARRANGEMENT OF CONDUCTORS

This, with 3.2 amperes, was reduced to 2,900 ampere-turns, the *remaining* 2,900 ampere-turns per pole-piece being supplied by the lagging current in the armature winding. The 12-pole armature has 576 total turns, or 48 per pole-piece; but these 48 turns per pole-piece belong to three different phases, hence there are 16 turns per pole-piece per phase. The maximum ampere-turns per phase are

$$16 \times 138 = 2200 \text{ ampere turns.}$$

In Figs. 419 and 420 are shown, diagrammatically, the arrangement of the conductors of the different phases in the armature slots of a three-phase rotary; and directly above, the corresponding curve of magneto-

motive force due to the currents in the armature conductors. Fig. 419 represents the instant when these relative current values in the phases A, B, and C are, respectively, 1, 0.5, and 0.5. In Fig. 420 these have become 0867, 0, and 0.867. Hence it is in Fig. 419 that one phase reaches the maximum value 1, and as there are six conductors per pole-piece per phase its maximum magnetomotive force may be represented by 6. But although, in Fig. 419, the corresponding maximum value of

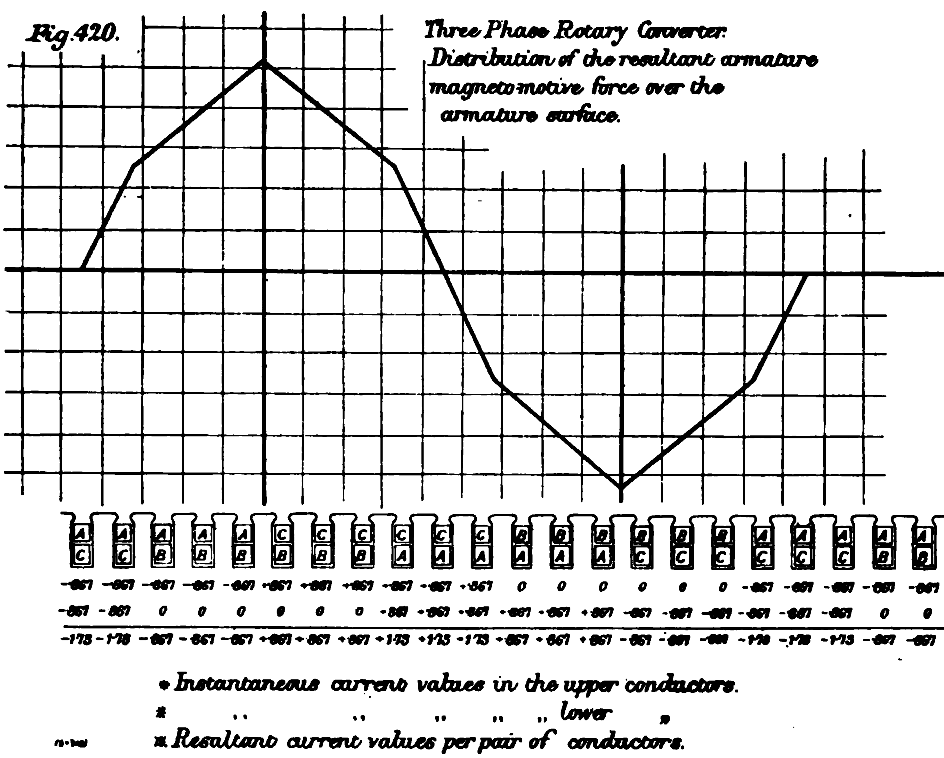


FIG. 420. DIAGRAM SHOWING DISTRIBUTION OF RESULTANT MAGNETOMOTIVE FORCE AND ARRANGEMENT OF CONDUCTORS

the magnetomotive force of the three phases is 9, it becomes 10.4, one-twelfth of a cycle later, at the instant represented by Fig. 420. Hence, in a three-phase rotary converter winding, the maximum magnetomotive force exerted by the armature conductors of all the phases, is, per pole-piece, $\frac{10.4}{6} = 1.73$ times as great as the maximum magnetomotive force per pole-piece per phase.

Now, for the case under consideration (the 900-kilowatt rotary), the value of 2200 ampere-turns per pole-piece was found for the maximum

magnetomotive force per phase. Therefore, the maximum resultant armature reaction for the three phases would be

$$1.73 \times 2200 = 3800 \text{ ampere-turns per pole-piece.}$$

But it is only in opposition to the flux at the very centre of the pole-face that the armature magnetomotive force would exert this strength. Aproaching both sides, it shades off towards zero, as may be seen from the curves of magnetomotive force distribution of Figs. 419 and 420, whereas the field spool against which it reacts is linked with the entire magnet core. In practice, these magnetomotive force curves would be smoothed out into something like sine curves. Were the pole arc to extend over the entire pole pitch, the average magnetomotive force exerted over the whole face of the pole shoe would be $\frac{2}{\pi}$ times the maximum value, a sine wave form being assumed for the distribution of the magnetomotive force about the circumference. As, however, the pole arc generally covers only from 65 per cent. to 70 per cent. of the pole pitch, the average magnetomotive force must be greater. In addition to this smaller pole arc there is the further circumstance to be considered, that the location of the armature magnetomotive force is more effective than that of the field ampere-turns; and this factor will also tend to increase the field ampere-turns that are necessary to compensate the armature ampere-turns.

In the above case, the field magnetomotive force amounts to 2900 ampere-turns, a value 24 per cent. smaller than the maximum magnetomotive force of the armature; or, conversely the maximum magnetomotive force of the armature is 1.31 times as great as the field magnetomotive force $\left(\frac{3800}{2900} = 1.31\right)$. To be able to estimate this with fair approximation, there are given in Table LXIII. an analysis of a series of test results leading up to its derivation. The factor by which the maximum armature magnetomotive force has to be divided in order to get the observed field ampere-turns, is given in the last column, and varies between 1.0 and 1.3, the average value being 1.15.

The difference between three-phase and six-phase windings, as regards the manner of distribution of the conductors of the different phases over the armature surface, has already been pointed out on page 329, and is illustrated diagrammatically in Fig. 379. Bearing in mind the difference there explained, it should be further noted that the so-called six-phase

winding gives a distribution of its armature magnetomotive force, in accordance with the diagrams for the magnetomotive force in induction motors which were shown and explained on pages 148 to 151. It is there shown that the three phases of such a winding exert a resultant

TABLE LXIII.—MAGNETOMOTIVE FORCE DATA OF ELEVEN THREE-PHASE ROTARY CONVERTERS

Rated Output in Kilowatts.	Speed in Revolutions per Minute.	Number of Poles.	Cycles per Second.	Commutator Voltage.	Armature Turns per Pole-Piece.	Observed. Field Ampere Turns for Minimum Current at No Load. A	Observed. Amperes per Ring at No Load, and no Field Excitation.	Observed. Amperes per Conductor at No Load, and no Field Excitation.	Maximum Magnetomotive Force per Pole, Corresponding to Preceding Column B	Ratio of B; A.
200	375	8	25	125	30	4150	1400	200	4900	1.17
200	600	6	30	510	84	3880	335	64.5	4450	1.15
50	750	4	25	125	31.5	5860	800	230	6000	1.02
120	900	4	30	550	72.6	4120	292	84	2500	1.22
150	750	4	25	600	96	7810	375	108	8600	1.1
300	532	6	26.6	550	72	4650	510	98	5750	1.23
250	750	4	25	550	60	4290	385	111	5500	1.28
100	1200	6	60	550	72	5650	555	106	6300	1.11
75	1200	6	60	550	99	4580	305	59	4800	1.04
250	500	6	25	550	72	4070	435	83	4900	1.2
100	750	4	25	125	24	4850	1030	300	5900	1.22

magnetomotive force, whose maximum value is equal to twice the maximum value of the magnetomotive force per phase. But by Figs. 419 and 420, on pages 384 and 385 *ante*, it has been shown that in the winding of the ordinary three-phase rotary converter (when the windings of the different phases overlap), this maximum value is only 1.73 times the magnetomotive force per phase. A six-phaser will, therefore, give equally effective response to field variations, with but $\frac{1.73}{2.00}$, or 87 per cent. as great an incoming current, as will a three-phase rotary

converter. This is a distinct advantage even for the shunt-wound and for the compound-wound rotary, but it is still more important in the case of the series rotary, and for the rotary without field excitation (which will shortly be discussed), since the chief objections to these latter types relate to the large incoming current due to absence of control of field excitation, except by means of armature reactions.

The choice of as many turns per pole-piece on the armature as good constants, in other respects, will permit is, of course, conducive in all types of rotaries to the best result from the standpoint of securing the required magnetomotive force from the armature with as little idle current as possible.

By similar methods the magnetomotive force relations may be analysed from the phase characteristics with load. Under these conditions, *i.e.*, with current delivered from the commutator, there are further considerations: The demagnetising influence of the commutated current may be neglected, as the brushes remain at the neutral point, and even the *distorting* influence upon the magnetic distribution may be considered to be substantially offset by the overlapping *energy* component of the incoming alternating current. The main difference appearing in the analysis of the phase characteristic with load, is that the energy component, except with great weakening or strengthening of the normal field, will be a very appreciable component of the total resultant incoming alternating current. Thus in Fig. 416 (page 381, *ante*), the upper curve represents the phase characteristic with full-load output of 1100 amperes at 115 volts from the commutator. At normal field of 2750 ampere-turns, the amperes input per collector ring are 1030. Reducing the field excitation to zero increases this incoming current to 1290 amperes. The output is 125,000 watts.

The internal losses under these conditions of full-load output and zero field excitation, are approximately as follow:

	Watts.
Total armature C^2R loss	5,000
Bearing and all brush friction	2,700
Core loss	2,700
Brush C^2R losses	3,500
Total internal loss	13,900
Watts output	125,000
Total watts input	138,900

Total watts input per phase ...	... ...	46,300
Voltage per phase ...	... ...	75 volts.
Energy component of current per phase in armature	...	616 amperes.
Observed current input per collector ring	... ...	1290 „
„ „ in armature winding	... ...	745 „
Magnetising component $= \sqrt{745^2 - 616^2} =$	... ...	406 „

The armature has a six-circuit single winding with 180 total turns; therefore, 10 turns per pole-piece per phase.

Magnetising current per turn $= \frac{406}{3} = 135$ amperes.

Maximum magnetomotive force per phase $= \sqrt{2} \times 135 \times 10 =$ 1900 ampere turns.

Hence maximum of resultant magnetomotive force of armature per pole-piece $= 1.73 \times 1900 = 3300$ ampere-turns.

Field ampere-turns (observed at no load) =	... ...	2750
Ratio $\frac{3300}{2750} =$	... ...	1.2

"Surging" Effect.—Reference has been made to the "surging" effect in rotary converters as being chiefly responsible for the discrepancy between the observed current input when the field is adjusted for minimum input, and the energy current input. This additional current is of the nature of an interchanging current amongst the generators and rotary converters. When, in the first place, the source of power driving the generator has not a constant angular effort, the flywheel may not be sufficiently large to make the angular velocity uniform throughout the revolution.

The rotary converter, to remain strictly in synchronism, must respond perfectly to those changes in angular velocity. Of course, it cannot do so perfectly, so the result is that at one instant it lags behind by a more or less small fraction of an alternation, (distance from mid-pole-face position), and takes more current; then it accelerates more rapidly, gains on the generator, and swinging too far forward, on account of its momentum, acts for the instant as a generator, returning current to the source of its supply. This is the nature of the superposed current above referred to.

According to the degree of unevenness of the angular speed of the generator, and to the absolute and relative inertia of the moving parts of the generators and rotary converters, this superposed swinging motion may be more or less great; and may, either between generators and rotary, or between rotaries, develop into sympathetic swings of considerable magnitude, leading in some cases to falling out of phase, but more often

to serious and rather destructive sparking at the commutator, due to the pulsations. As already pointed out, these troubles may be remedied in practice by employing copper coils or plates specially located between pole-pieces; or more easily, but less economically and effectively, by using wrought-iron pole-pieces of the highest practicable conductivity, with small clearance between pole-face and armature.

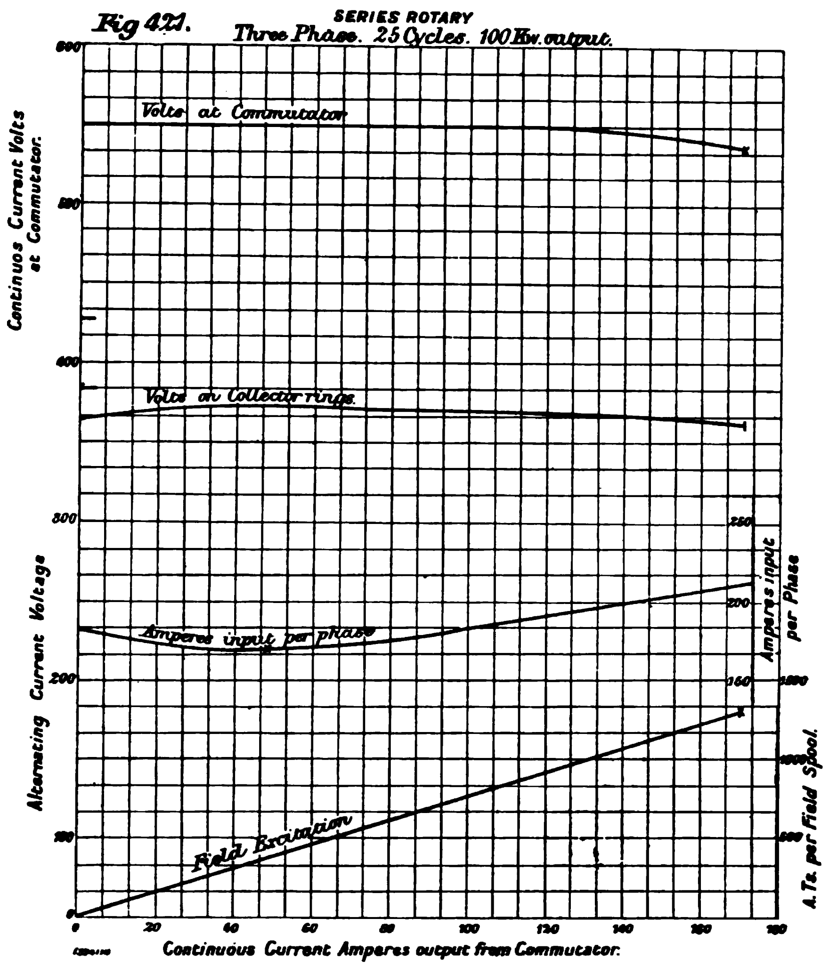


FIG. 421. CURVES FOR A 550-VOLT, 100-KILOWATT, SERIES ROTARY

Compound-Wound Rotary.—The purpose of the compounding coil (series winding) has already been set forth (see page 350), and it merely remains to state that in practice it has been found to distinctly diminish the tendency to stability when the "surging" effect is present to any extent. Nevertheless, it is an aid to automatic phase regulation, being, of course, more especially valuable where quick changes of load are

constantly occurring, as in the operation of tramways. For gradually varying load, pure shunt excitation with hand regulation is more satisfactory, unless the generator is driven with an extremely uniform angular motion.

The current delivered from the commutator of a rotary converter is never very uniform; it has always a superposed alternating-current

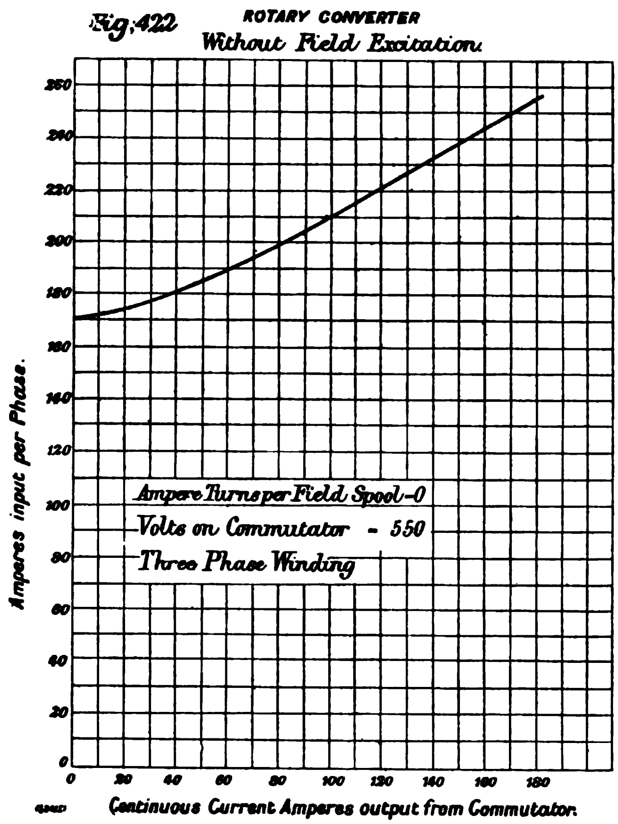


FIG. 422. CURVES FOR A 550-VOLT, 100-KILOWATT ROTARY, WITHOUT FIELD EXCITATION

component, which may be readily demonstrated by sending such a commutated current through a reactance coil of sufficient inductance, when there may be observed across the terminals of the coil (by an alternating-current voltmeter) a difference of potential many times in excess of the CR drop.[1] Although this is best observed by means of the drop across it, such a reactance coil tends to eliminate these

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[1] See *Journal*, Institution of Electrical Engineers, vol. xxvii., page 710, 1898.

variations, and they are much less than when no inductance is in circuit. A compound winding will, to a certain degree, have this same effect; and while the difficulties attending its use are probably partly due to this effect, it should at the same time tend in some measure to make the commutated current more free from superposed variations. The series winding is cut out when starting up from the continuous-current side, and this is conveniently accomplished by a double-throw switch, which in one position connects the junction of the series winding and the negative brushes to the starting rheostat, and in the other position connects this point with the equalising bar.

Series Rotary.—The shunt winding may be dispensed with altogether in a rotary converter, the excitation being supplied by the series winding alone. The conditions, however, are not satisfactory, as the excitation is controlled entirely by the load current; and from what we have learned by a study of phase characteristics, such wide variation of excitation cannot be made to give an economical power factor for any extended range of load. Curves taken upon a 550-volt, 100-kilowatt rotary, operated in this manner, are given in Fig. 421, on page 390.

Rotary without Field Excitation.—A rotary with no field winding supplies its excitation by virtue of the magnetising effect of the lagging currents flowing through its armature, and which enter from the collector rings. In Fig. 422 is given a curve of the alternating-current, in terms of the continuous-current output for the above-mentioned 100-kilowatt rotary when operated with no field excitation. In this case, the excitation of the generator was raised from 5,500 ampere-turns per spool, when no amperes were delivered from the commutator of the rotary converter, up to 7000 ampere-turns per spool at full load amperes delivered from the commutator of the rotary converter. This served to maintain the commutator potential of the rotary constant at 550 volts, throughout the whole range of load. This increased excitation of the generator was necessary, as it also was of only 100-kilowatt capacity; and the large demagnetising magnetomotive force of the lagging armature current acting against its own impressed field, required to be overcome by the increase of field excitation from 5500 to 7000 ampere-turns per spool. Such rotaries without field windings have, however, actually been employed commercially.

The advantage of having, for rotaries of this type, a very strong armature, even to the sacrifice of the most favourable values for other

constants, will now be clearly seen. The armature winding will thereby be enabled to supply the required magnetomotive force with less excessive magnetising currents from the source of supply. The use of six collector rings (so called six-phase), has in this respect an advantage of 14 per cent. for a given armature and winding over the ordinary method with three rings.

Relative Advantages of Rotary Converters and Motor Generators

A great deal has been written on the question of the relative advantages of rotary converters and motor generators. It may be shown by an analysis of the properties of the rotary converter, that only in cases where the distance of transmission is comparatively short, the transmission voltage high, and the outlay for cables relatively great, is it practicable to operate rotary converters satisfactorily with respect to automatic control of the commutator voltage for practically constant voltage at all loads. The range of cases in which 5 per cent. to 10 per cent. automatic over-compounding from no-load to full is practicable is still more restricted. Even with a low resistance per phase it is necessary to provide large, expensive, and wasteful auxiliary reactance coils, in order to obtain satisfactory control by automatic phase adjustment; and for anything more than a very low resistance per phase there is soon reached a value of the reactance beyond which it is ineffective in producing improved conditions in this respect. In fact, with shunt-excited rotary converters, and even with a small percentage of series-winding, reactance makes the regulation still worse.

In long-distance transmission systems, where one must, from economical considerations, have 20 per cent. voltage drop, and even more, in the high-tension line, the necessary conditions are not fulfilled, and motor generators should be employed.

The continuous-current generator of such a motor generator set is, so far as relates to voltage regulation, the equivalent of a generator driven direct from an engine with the same speed regulation as that of the engine at the power-house. It may be shunt-wound, or it may be compounded for constant terminal voltage at all loads, or for a voltage increasing with the load. The amount of loss in the high-tension transmission line has no influence upon its operation.

Thus, in a case where motor generators are employed, one will

expend just as much for transmission cables as is necessary to obtain maximum economy, when estimated on the basis of the interest on this capital outlay for cables and the cost of producing the energy dissipated in the transmission line. But when rotary converters are used, it becomes practically impossible to obtain satisfactory automatic control of the commutator voltage with more than from 5 per cent. to 10 per cent. resistance drop in the high-tension line, and a thoroughly excellent result is only to be obtained by a very low resistance drop. Hence, a successful plant, with rotary converter, in the sub-stations, only becomes economically possible where the length of transmission is not great, or where a higher voltage is employed for transmission than would be required for the operation of motor generators. Although these considerations have not been very prominently emphasised by writers in comparing the two systems, they corroborate the generally-accepted view that the use of rotary converters is attended with higher efficiency in operation than is the case where motor generators are used. But they are at variance with another generally-accepted conclusion, viz., that a lesser first cost may be attained by the use of rotary converters. This may sometimes be the case for short distances, but for other conditions the greatly increased outlay necessary for cables will generally lead to the opposite result. Thus the question resolves itself, for any given case, into comparing the greater interest on capital expenditure when rotary converters are used against the cost of operation with motor generators. For conditions where this comparison shows little to choose between the two systems, motor generators should be employed on the score of their great superiority in convenience of operation.

PART IV

ALTERNATORS

ALTERNATORS

THE method of designing alternators here set forth is founded upon experimental data, and it is not proposed to encumber its presentation with any superfluous theoretical considerations.[1] Single and polyphase machines will often be considered together, it being quite unnecessary to devote entirely separate sections to them.

The controlling consideration in the design of commutating dynamos relates to the securing of sparkless commutation, and this imposes limitations, chiefly with respect to the permissible inductance of a coil between adjacent commutator segments, and the permissible armature reaction expressed in ampere turns per pole-piece on the armature.

In alternator design these limitations do not exist, so far as relates to their influence upon commutation, but they still in a large measure require to be observed in relation to their influence upon other matters affecting the general performance of the machine.

An alternator has to be designed for a given periodicity, and generally the speed of the engine or turbine is fixed from mechanical considerations; hence, if the alternator is to be direct-driven, the number of poles is fixed by these two values—the periodicity and the speed—and the designer has no freedom of choice in this respect. He must, nevertheless, make the armature strength and inductance sufficiently small to comply with specified standards of regulation. The number of poles being fixed, the armature strength can only be limited by limiting the number of turns thereon; but the inductance may also be maintained low, by transmitting the required total magnetic flux at the

[1] In fact, the method is admittedly slightly defective from the theoretical standpoint. This, however, is in the authors' opinion justified by the great gain in simplicity and utility thereby obtained. Nevertheless, although slight theoretical errors are introduced, much larger theoretical and practical errors, common to many other methods of designing alternators, have been avoided, and this is the distinguishing feature of the method.

greatest permissible flux density, and by subdividing the winding as much as practicable. From a mechanical standpoint, the best results are secured by the projection core construction; and, by due care in proportioning, machines of excellent electrical properties as to regulation may be obtained.

Ironclad armatures may be subdivided into uni-slot and multi-slot armatures. In the former, the conductors are concentrated in one slot per pole per phase; in the latter, they are more or less distributed in many slots per pole. These slots may be spaced at equal distances around the periphery, or more or less grouped, according to circumstances. This method of designating types is illustrated in Fig. 423.

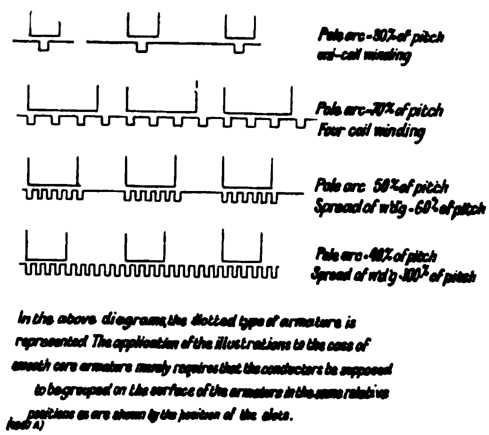


FIG. 423. DIAGRAM OF UNI-SLOT AND MULTI-SLOT ARMATURES

The number of poles having been determined from the speed and periodicity, the next step is to consider the number of ampere turns per pole to be permitted upon the armature. Some designers advocate fairly strong armatures, reasoning that this obviates the necessity of automatic circuit-breaking devices, with the attending difficulties of adapting them to use on high-tension circuits of considerable capacity; since strongly reactive armatures, even if short-circuited, will not, with normal excitation, carry a dangerously high current. At short circuit the armature current opposes the field magnetisation, and the voltage falls, thus rendering it impossible for any excessive demand to be put on the steam-engine or other source of motive power. This is seen at a glance from Figs. 424 and 425, where, for constant excitation, and in terms of the amperes output, the curves of voltage and of kilowatts

output are given for a generator with so strong an armature reaction that, even on short circuit, the armature current only increases to 50 per cent. above its normal value.

Fig. 425 shows that, if the field excitation remain constant at the value required to maintain the normal voltage at the rated output, it is impossible to load the generator up to more than 205 kilowatts; hence the steam-engine or other source of power is protected from severe strains, as well as the generator.

Such a machine, with strong armature, is characterised by the small amount of iron in its magnetic circuit, in consequence of which the copper turns are short, and the amount of copper employed is also by

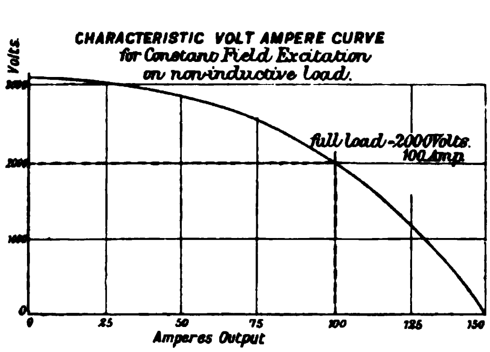


Fig. 424.

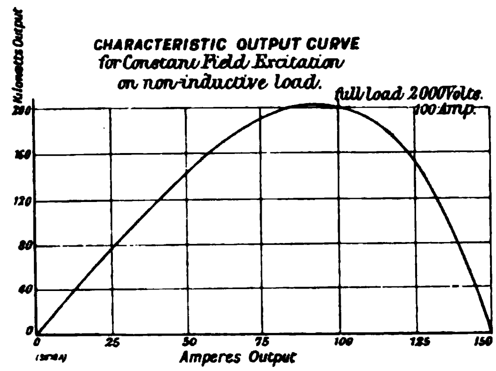


Fig. 425.

Curves of Voltage and Kilowatt Output

no means excessive: hence the design is very economical of material, and compact. The chief disadvantage, however, is the inferior inherent regulation.[1]

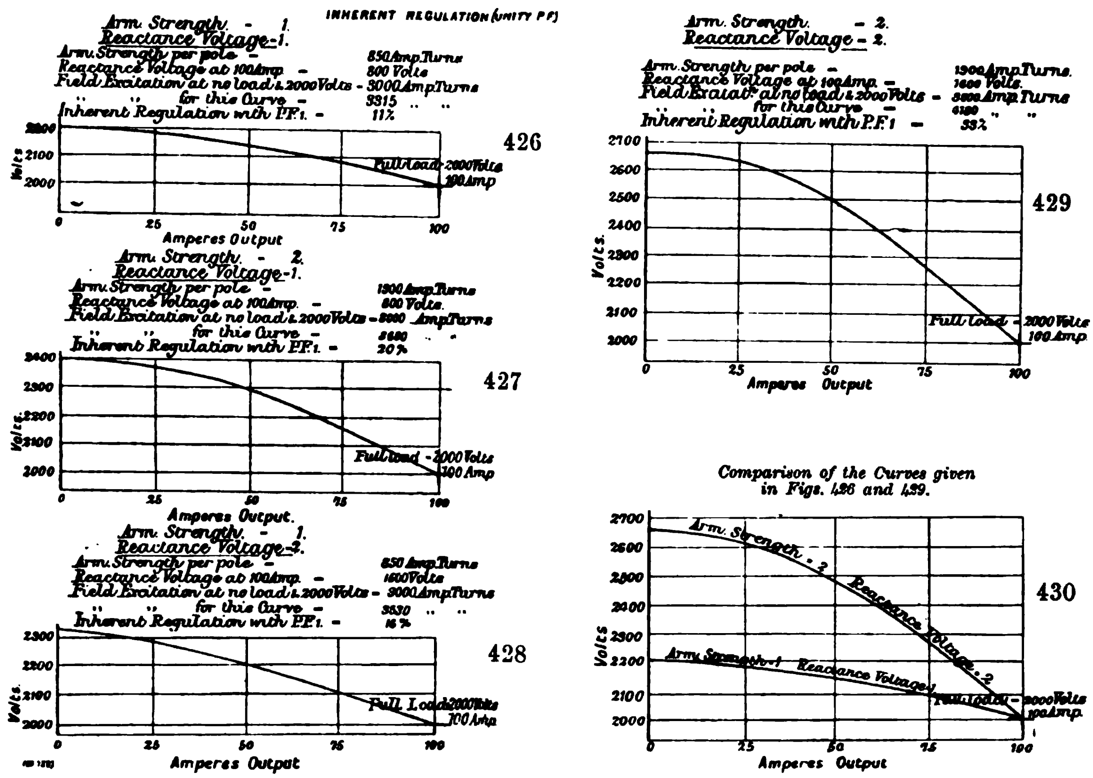
Inherent Regulation

We may define inherent regulation as the percentage variation in the voltage of the machine, from no-load to full-rated amperes output, when the field excitation remains unchanged at such a value as to give the rated voltage at the rated amperes output. The inherent regulation will be different, according to the nature of the external load. It should preferably be quoted for a non-inductive external load (*i.e.*, power factor = 1), and also for a completely-inductive external load

[1] With the advent of good automatic pressure regulators external to the machine, the inherent regulation becomes of less importance, and machines with strong armatures become permissible.

(power factor = 0). The latter condition can be approached in commercial tests with sufficient exactness for practical purposes.

In Fig. 426, the curve given shows the inherent regulation, with unity power factor, for a machine with low armature strength and low inductance. Fig. 427 shows the effect upon the regulation of doubling the armature strength, but retaining the same inductance (in practice, of course, difficult to accomplish, but nevertheless valuable as showing



FIGS. 426 TO 430. INHERENT REGULATION CURVES

the way such changes tend to affect the regulation). In Fig. 428, the armature strength is restored to its original low value, but the inductance is doubled. Fig. 429 shows the case of doubling the original value, both of the armature strength and of the inductance. In Fig. 430, the curves of Figs. 426 and 429 are brought together for comparison.

THE INHERENT REGULATION FOR ZERO POWER FACTOR

For power factor = 0, the inherent regulation becomes a straight line, except in so far as magnetic saturation sets in, and is entirely

dependent upon the value of the armature strength; being at the same time independent of the value of the reactance, except as regards modifications of quite a secondary order of importance.

In Fig. 431 are given curves of the inherent regulation for zero power factor, corresponding to the two cases where Fig. 430 shows the inherent regulation for unity power factor.

Excitation Regulation

Excitation regulation may be defined as the percentage increase, above that for no-load, required in the excitation of a machine in order that, at rated amperes output, it may maintain the rated voltage. The

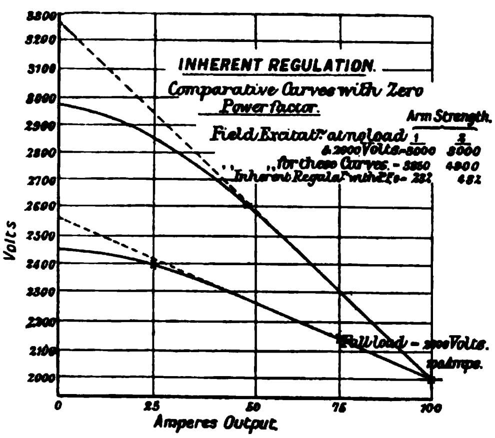


Fig. 431.

Curves of Inherent Regulation

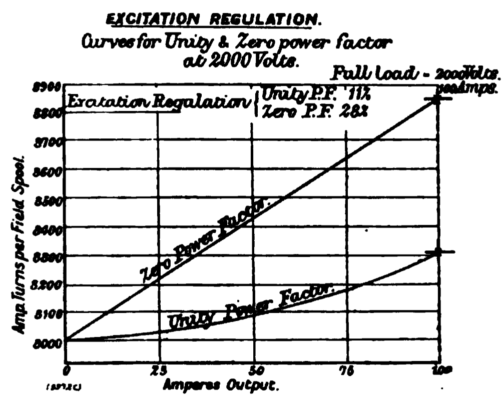


Fig. 432.

Curves of Excitation Regulation

excitation regulation is also a function of the power factor of the external load. In Fig. 432 are given two curves of excitation regulation, one for unity power factor and the other for zero power factor. They are for the same machine of which Fig. 426 gave the inherent regulation curve.

The values of the excitation regulation corresponding to all the above cases are tabulated on the following page, and the numerical values for the inherent regulation are reproduced for comparison.

This Table is only intended to give a general idea of the influence that the variations, in the different designs indicated, would have upon the final results. The most important point to be learned from the table is that for cases where, with fairly good excitation and inherent regulation, it is desired that the regulation shall be more or less independent of the value of the power factor of the external load, one must work in the direction indicated by column 3, namely, to have the smallest possible armature strength (as expressed in ampere-turns per

pole-piece on the armature), and at the same time the highest possible reactance consistent therewith. This is not an impracticable combination, except from the mechanical standpoint. An armature, with very few turns, completely buried below the surface of the iron, could be proportioned to have high reactance voltage, notwithstanding the small number of turns. On non-inductive loads, however, it would not show (see column 1) nearly so good regulation as with the same number of armature turns in wide open slots, or (better still from this standpoint) secured to the armature surface; or, again, other arrangements might be made calculated to lessen the inductance; such, for instance, as dispensing with the armature iron altogether, as has been done in some designs.

TABLE LXIV.—VALUES OF EXCITATION REGULATION

——	Armature Strength 1. Reactance Voltage 1.	Armature Strength 2. Reactance Voltage 1.	Armature Strength 1. Reactance Voltage 2.	Armature Strength 2. Reactance Voltage 2.
	per cent.	per cent.	per cent.	per cent.
Excitation regulation for unity power factor	11	21	18	39
Excitation regulation for zero power factor	28	63	28	63
Inherent regulation for unity power factor	11	20	16	33
Inherent regulation for zero power factor	23	48	23	48

Hence it follows that the nature of the load for which the generator is intended, and the method adopted for regulating the excitation, control the choice of lines on which to base the design. Enough has now been said to make it plain that the inherent regulative properties of an alternator will be improved by employing an initial field of high magnetomotive force to obtain the rated voltage at no-load, since the armature interference must be proportionately less the stronger the impressed magnetomotive force is in comparison with the interfering armature magnetomotive force and reactance. On the whole, though it will be now well understood that no sweeping assertion should be made, rather better results will generally be obtained by limiting the armature reaction and inductance to fairly low values. It is, at first sight, a curious result that low armature inductance improves the regulation on non-inductive loads, but does not in itself improve the regulation on inductive loads. Good regulation for inductive loads is secured by low armature strength, as expressed in ampere turns per pole-piece upon the armature. Decreasing the number of turns tends to keep the coils of moderate depth, thus also leading to better thermal conditions. On the score of safety at short-circuit, it may be said that any well-designed

alternator is capable of carrying three or four times its rated full-load current for a minute or more, and the armature reaction cannot economically be made so low as to permit more current than this, even at short-circuit. The force of the argument in favour of armatures with few turns of low inductance is weakened by the necessity of also protecting the source of power. Hence it may be said that the automatic cut-outs, now available for high-tension circuits, serve to protect the line, instruments, switchboards, and the source of motive power, rather than the alternator. The authors are of the opinion that automatic pressure regulators external to the alternator afford good promise of a solution to the question.

Calculation of the Inductance of the Windings of Alternators

Inductance is expressed in henrys, and a coil has an inductance of one henry when it is of such dimensions that a current of one ampere sets up a magnetic flux of such a magnitude that the product of the number of lines linked with the coil, multiplied by the number of turns in the coil, is equal to 100,000,000. If the coil has but one turn, then its inductance in henrys becomes 10^{-8} times the number of lines linked by the turn when one ampere is passing through it. And since one ampere passing around two turns sets up twice as great a flux, and as this flux is linked with both of the turns, the product of the flux multiplied by the turns will be four times as great as with one turn. The inductance of a coil is proportional to the square of the number of turns.

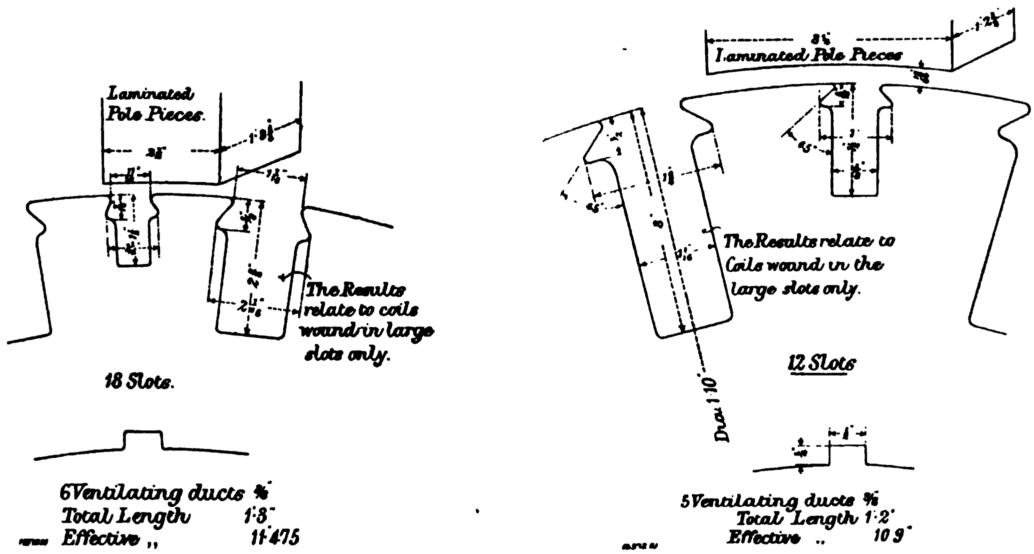
Measurements have been made of the inductance of many alternating current windings in slots of various proportions. The values derived, expressed in terms of the flux per R.M.S. ampere turn and per inch gross length of the armature laminations, have, for ironclad alternators of customary types, been found to generally lie between the limits of 20 and 50 C.G.S. lines for the position of maximum inductance, and between the limits of 10 and 35 in the position of minimum inductance. For rough trial values, one might take :—

For position of maximum inductance 40 C.G.S. lines per R.M.S. ampere turn, and per inch length of armature laminations.

For position of minimum inductance 25 C.G.S. lines per R.M.S. ampere turn, and per inch length of armature laminations.

And for average value, 33 C.G.S. lines per R.M.S. ampere-turn, and per inch length of armature laminations.

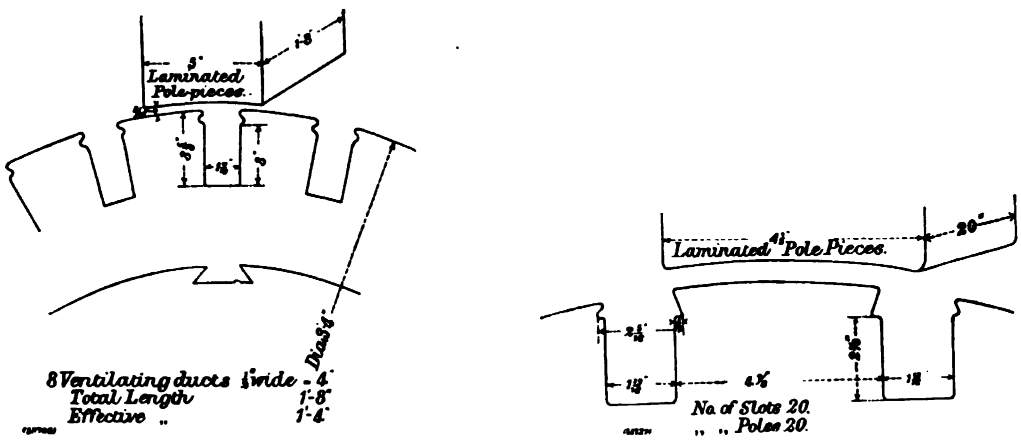
Fig. 433.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	18	—	—
Number of armature coils ...	9	—	—
Periodicity used in tests ...	125	—	—
Reactance	...	1530 volts ÷ 65 amperes = 23.5 ohms	900 volts ÷ 65 amperes = 13.84 ohms
Reactance per coil	...	2.62 ohms	1.54 ohms
∴ Inductance per coil... ...	...	0.00333 henry	0.00196 henry
Turns per coil	32	—	—
∴ Inductance for one turn ...	...	0.00000328 henry	0.00000193 henry
∴ Flux per ampere turn ...	...	328 C.G.S. lines	193 C.G.S. lines
Length of laminations... ...	15 in.	—	—
∴ Flux per ampere turn per inch	...	21.8 C.G.S. lines	12.8 C.G.S. lines



FIGS. 433 AND 434. SLOT INDUCTANCE

Fig. 434.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	12	—	—
Number of armature coils ...	6	—	—
Periodicity used in tests ...	125	—	—
Reactance of total armature ...	...	2080 volts ÷ 43.5 amperes = 47.8 ohms	1100 volts ÷ 43.5 amperes = 25.25 ohms
Reactance per coil	...	7.98 ohms	4.2 ohms
∴ Inductance per coil... ...	...	0.00102 henry	000532 henry
Turns per coil	46	—	—
∴ Inductance for one turn ...	...	0.00000478 henry	0.0000025 henry
∴ Flux per ampere turn ...	...	478 C.G.S. lines	250 C.G.S. lines
Length of laminations... ...	14 in.	—	—
∴ Flux per ampere turn per inch of length	...	34.1 C.G.S. lines	17.8 C.G.S. lines

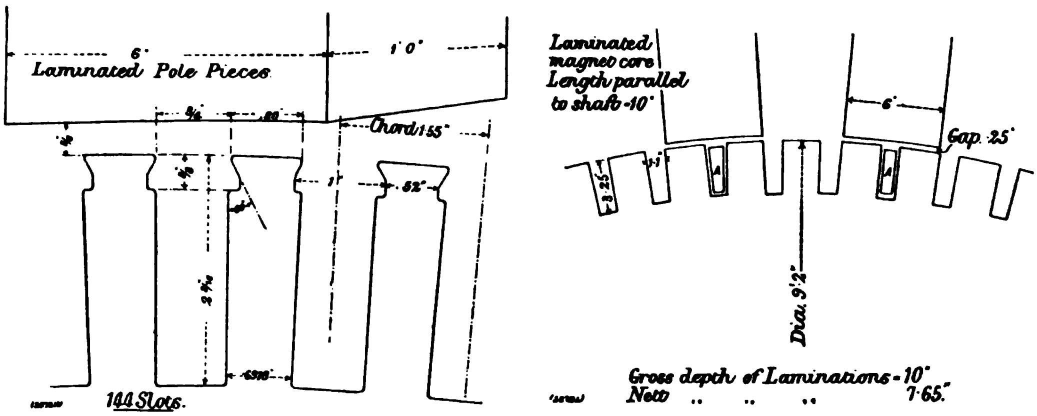
Fig. 435.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	16	—	—
Number of armature coils ...	24	—	—
Periodicity used in tests ...	60	—	—
Reactance of one branch—*i.e.*, 8 coils	...	120 volts ÷ 500 amperes = 0.24 ohms	96 volts ÷ 500 amperes = 0.192 ohm
Reactance per coil	...	0.03 ohm	0.024 ohm
Inductance per coil	...	0.0000795 henry	0.0000635 henry
Turns per coil	4	—	—
∴ Inductance per turn ...	...	0.00000495 henry	0.00000396 henry
∴ Flux per ampere turn ...	...	495 C.G.S. lines	396 C.G.S. lines
Length of laminations... ...	20 in.	—	—
∴ Flux per ampere turn per inch of length	...	24.8 C.G.S. lines	19.8 C.G.S. lines



FIGS. 435 AND 436. SLOT INDUCTANCE

Fig. 436.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	20	—	—
Number of armature coils ...	10	—	—
Periodicity used in tests ...	60	—	—
Reactance of total armature ...	...	105 volts ÷ 10.4 amperes = 10.1 ohms	103.5 volts ÷ 16.2 amperes = 6.39 ohms
Reactance per coil	...	1.04 ohms	0.639 ohm
∴ Inductance per coil	...	0.00277 henry	0.0017 henry
Number of turns per coil ...	24	—	—
∴ Inductance for one turn ...	...	0.00000482 henry	0.00000295 henry
∴ Flux per ampere-turn ...	...	482 C.G.S. lines	295 C.G.S. lines
Length of laminations... ...	20 in.	—	—
∴ Flux per ampere-turn per inch	...	24.1 C.G.S. lines	14.7 C.G.S lines

Fig. 437.	——	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	24	—	—
Number of armature coils ...	36 sets of 2 each	—	—
Periodicity used in tests ...	60	—	—
Reactance of 12 sets of coils ...	... ...	109 volts ÷ 30.3 amperes = 1.33 ohm	103 volts ÷ 77.5 amperes = 3.61 ohms
Reactance per set of 2 coils ...		0.3008 ohm	0.1108 ohm
∴ Inductance per set of 2 coils	...	.000798 henry	0.000294 henry
Number of turns per set of 2 coils	12	—	—
∴ Inductance for one turn ...	...	0.00000555 henry	0.00000204 henry
∴ Flux per ampere turn ..	...	555 C.G.S. lines	204 C.G.S. lines
Length of laminations... ...	16 in.	—	—
∴ Flux per ampere turn per inch	...	34.7	12.7



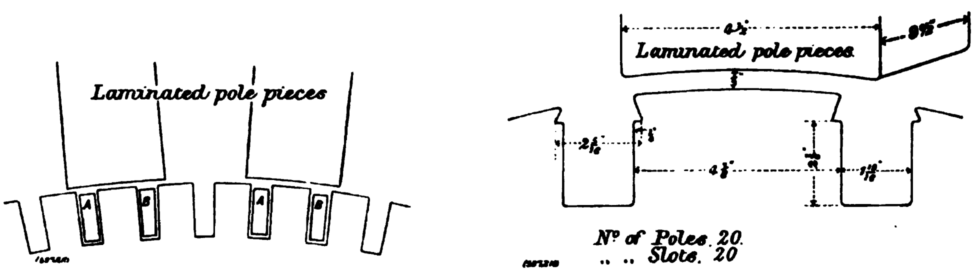
FIGS. 437 AND 438. SLOT INDUCTANCE

Fig. 438.	——	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	32	—	—
Number of coils in test ...	16	—	—
Periodicity used in test ...	25	—	—
Total reactance of coils in test...	...	385 volts ÷ 46 amperes = 8.36 ohms	370 volts ÷ 88 amperes = 4.2 ohms
Inductance of coils in test ...	...	0.554 henry	0.0279 henry
Number of coils tested ...	16	—	—
Number of turns per coil ...	24	—	—
∴ Inductance per turn ...	...	0.00006 henry	0.00000303
∴ Flux per ampere turn ...	...	600 C.G.S. lines	303 C.G.S. lines
Length of laminations ...	10 in.	—	—
∴ Flux per ampere turn per inch	...	60.0 C.G.S. lines	30.3 C.G.S. lines

Coil AA consists of 24 turns in series. Position shown is that of maximum inductance. The intermediate slots may be considered empty, as their windings were not connected up.

Fig. 439.	——	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	32	—	—
Number of armature coils in test	16	—	—
Periodicity used in test ...	25	—	—
Total reactance of coils tested...	...	390 volts ÷ 24.7 amperes = 15.8 ohms	388 volts ÷ 36.7 amperes = 10.6 ohms.
Inductance of coils tested ...	...	0.105 henry	0.07 henry
Number of coils tested ...	Taken as 16	—	—
Number of turns per coil ...	48	—	—
∴ Inductance per turn ...	...	0.00000285 henry	0.00000190 henry
∴ Flux per ampere turn ...	...	285 C.G.S. lines	190 C.G.S. lines
Length of laminations... ...	10 in.	...	—
∴ Flux per ampere turn per inch	...	28.5 C.G.S. lines	19.0 C.G.S. lines

This is the same magnetic structure as in the preceding figure; but two coils, AA, BB, are connected in series. The position shown is that of maximum inductance. AA, BB, each consist of a coil of 24 turns in series, called coil AA, BB. The intermediate slots may considered empty, as their windings were not connected up.



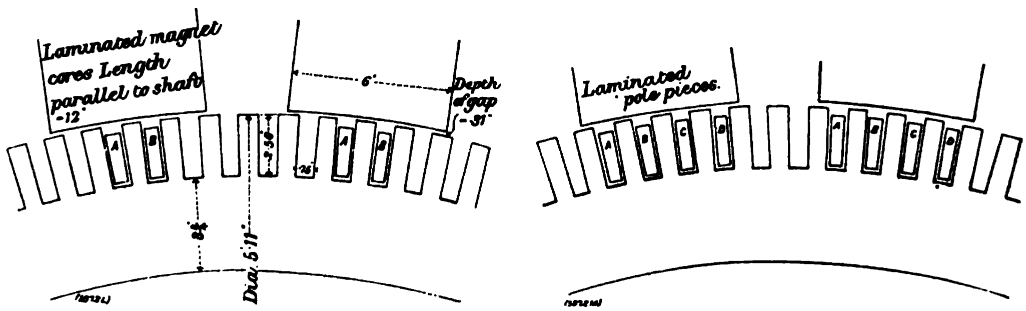
FIGS. 439 AND 440. SLOT INDUCTANCE

Fig. 440.	——	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	20	—	—
Number of armature coils ..	10	—	—
Periodicity used in tests ..	60	—	—
Reactance of total armature ...	...	196 volts ÷ 8.25 amperes = 23.8 ohms	186 volts ÷ 12 amperes = 15.6 ohms
Reactance per coil	...	2.38 ohms	1.56 ohms
Inductance per coil	...	0.00634 henry	0.00415 henry
Turns per coil	48	—	—
Inductance for one turn ...	...	0.00000275 henry	0.00000180 henry
Flux per ampere turn ...	...	275 C.G.S. lines	180 C.G.S. lines
Length of laminations ...	$9\frac{1}{2}$ in.	—	—
Flux per ampere turn per inch of length	...	28·9 C.G.S. lines	19.0 C.G.S. lines

Fig. 441.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	24	—	—
Number of armature coils in test	12 coils of 24 turns each	—	—
Periodicity used in test ...	30	—	—
Reactance of coils tested ...	...	133 volts ÷ 24 amperes = 5.53 ohms	87 volts ÷ 27 amperes = 3.22 ohms
Inductance of coils tested ...	...	0.029 henry	—
Turns per coil—*i.e.*, test coil ...	24	—	—
∴ Inductance per turn ...	...	0.0000042 henry	0.00000245 henry
∴ Flux per ampere-turn ...	...	420 C.G.S. lines	245 C.G.S. lines
Depth of laminations	12 in.	—	—
∴ Flux per ampere-turn per inch	...	35 C.G.S. lines	20.4 C.G.S. lines.

Coil AA = 12 turns in series. Gross Depth Laminations = 12 in.
Coil BB = 12 turns in series. Net depth laminations = 8.5 in.

Consider coils AA and BB in series to make up one coil of 24 turns called coil AA, BB. Position shown is that of maximum inductance. The intermediate slots may be considered empty, as their windings were not connected up.



Figs. 441 AND 442. SLOT INDUCTANCE

Fig. 442.	—	Position of Maximum Inductance.	Position of Minimum Inductance.
Number of poles	24	—	—
Number of armature coils in test	12 coils of 48 turns each	—	—
Periodicity used in test ...	30	—	—
Total reactance of coils tested ..	—	288 volts ÷ 24.5 amperes = 11.8 ohms	230 volts ÷ 28 amperes = 8.2 ohms
Inductance tested	—	0.0626 henry	0.0435 henry
Number of coils tested ...	Taken as 12	—	—
Turns per coil	48	—	—
∴ Inductance per turn ...	...	0.00000226 henry	0.00000157 henry
∴ Flux per ampere turn ...	...	226 C.G.S. lines	157 C.G.S. lines
Length of laminations ...	12 in.	—	—
∴ Flux per ampere-turn per inch	...	19.0 C.G.S. lines	13.1 C.G.S. lines

This is the same magnetic structure as in the preceding figure, but four coils AA, BB, CC, and DD, are connected in series. Opposite successive pairs of poles are other coils similarly disposed, but the results will be expressed in terms of the one set of coils shown. The intermediate slots may be considered empty, as their windings were not connected up. The position shown is that of maximum inductance, AA, BB, CC, and DD each consist of a coil of 12 turns in series. Consider coils AA, BB, CC, DD to make up one coil of 48 turns in series called AA, BB, CC, DD.

But, of course, it is very desirable to consider each case by itself, and the experimental data given in Figs. 433 to 442, pages 404 to 408, will be of use for the purpose.

From such data as that of the preceding tests, it is possible, in designing a new machine, to make a fair estimate of its inductance. As an example of the process, the case may be taken of a uni-slot, 20-pole, ironclad armature, with 10 coils of 20 turns each. The length of the armature laminations, parallel to the shaft, may be taken as 15 in. After comparing the slot dimensions with the cases in Figs. 433 to 442, it is decided to assume an average inductance for all positions, of 30 lines per ampere

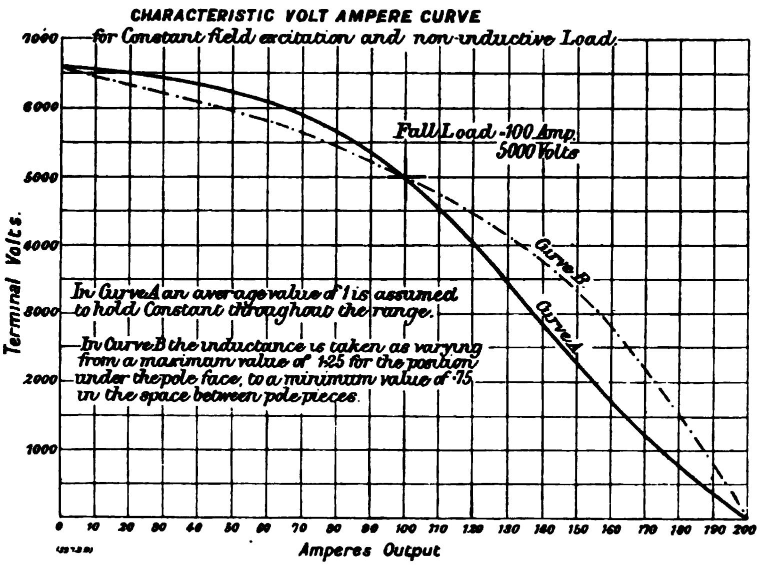


Fig. 443. Volt-Ampere Curve

turn and per inch length of armature lamination. Then the average inductance of one coil is: $20^2 \times 0.00000030 \times 15 = 0.0018$ henry.

And the inductance of the entire armature between collector rings (10 coils in series) $= 10 \times 0.0018 = 0.018$ henry.

If the periodicity of this machine were 80 complete cycles per second, then the reactance of the winding would be: $2\pi \times 80 \times 0.018 = 9.0$ ohms. And, at a current output of 200 amperes, the reactance voltage equals $200 \times 9.0 = 1800$ volts.

Whereas, in considering the inductance of the short-circuited coil in commutating generators, it is the value for the position of minimum inductance which possesses the chief interest; in the case of alternators, account must be taken of the inductance in all positions, from maximum

to minimum, in order to consider with exactness the performance of a machine under all circumstances. The reason for this will appear later. Here, however, may be given, without further explanation, characteristic volt-ampere curves for constant field excitation, and for non-inductive load. The first, curve A, Fig. 443, is calculated from the average value of the inductance. In the second, curve B of Fig. 443, approximate allowance is made for the variation of the inductance at different points of the curve, from its maximum to its minimum value.

Before proceeding to thoroughly practical applications of the methods of calculating these and similar curves and quantities, it is very necessary to clear up another point where our method is at variance with those in general use.

In such methods, one frequently finds the inductance of the alternator considered as a quantity quite as separable and independent as the inductance of the line, or of a reactance coil. In certain respects this is quite right; but care should be taken not to forget that there is, in an alternator, an impressed magnetic flux traversing the same iron core which is the seat of the inductance flux. Alternators have been analysed on the assumption that one could rightly represent the inductive armature as equivalent to a non-inductive armature, devoted solely to the work of generating energy by the mechanical passage of its conductors through an impressed magnetic field, plus a separate reactance coil, independent of the impressed magnetic field, and having an inductance equal to that of the armature. Fig. 444 represents this conception.

From this it has been said that the non-inductive armature must generate a voltage equal to the vector sum of the terminal voltage E_t, and the reactance voltage E_r; and this has been called the internal voltage E_i. Their relative values and phase relations are shown in Fig. 445.

When the load is non-inductive, the current is in phase with the terminal voltage, hence ϕ represents the angle of lag of the current behind the internal voltage. Diminishing the load, and consequently the armature current, reduces the reactance voltage, until, at no load, it becomes zero; and if the excitation remain unaltered, the terminal voltage finally comes to coincide, both in phase and magnitude, with the internal voltage. In Fig. 446 the diagram is given corresponding to a current output of one-half that taken for Fig. 445; and in

Fig. 447 the current (and hence also the E_r), having become zero, E_t has become equal to E_i.

The method goes on to the conclusion that, to obtain a terminal voltage of the value E_t, there must be present in the armature an impressed flux of the relative value E_i, and that

$$E_i = \sqrt{E_t^2 + E_r^2}.$$

This would be the case for such a circuit as that represented in Fig. 444, where an inductance is actually exterior to a non-inductive armature, but it will not be the case where the inductance is an

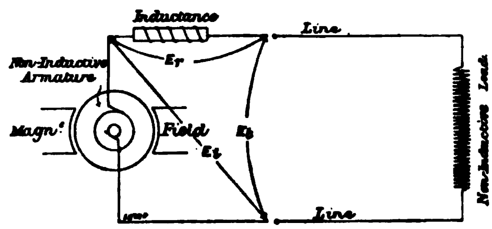


Fig. 444.

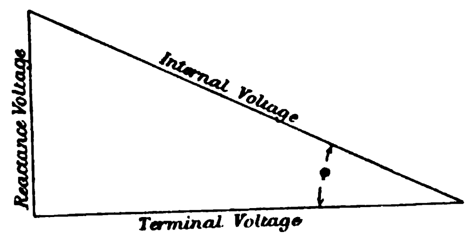


Fig. 445.

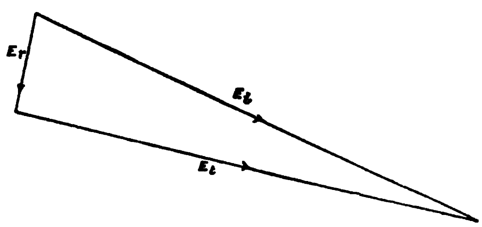


Fig. 446.

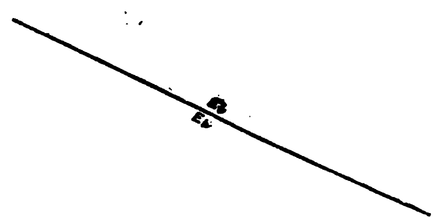


Fig. 447.

Diagrams Relating to Questions of Alternator Regulation

attribute of the very same conductor-wound armature, whose conductors, by being driven through an impressed magnetic field, generate the current delivered from the terminals at the voltage E_t. In such a case there is the reactance voltage E_r, set up by the flux of self-induction corresponding to the alternating current in the conductors, and the magnitude of this reactance voltage E_r corresponds to the magnitude of this flux of self-induction. There is also the terminal voltage E_t, set up by the cutting of the impressed flux by the armature conductors, and the magnitude of this terminal voltage E_t corresponds to the magnitude of this impressed flux.[1]

[1] The impressed flux is the actual flux which crosses the air gap from the pole-faces, and becomes linked with the armature coils; not the greater flux which is set up in the magnet core itself, a part of which latter completes its circuit by other paths, and does not enter the armature winding.

But the theory above commented on, and to which we take exception, led to the conclusion that for a given terminal voltage E_t and reactance voltage E_r, there would be necessary an impressed flux corresponding in magnitude to the internal voltage E_i; *i.e.*, greater than corresponded to the magnitude of the terminal voltage E_t, in the following ratio:—

$$\frac{E_i}{E_t} = \frac{\sqrt{E_t^2 + E_r^2}}{E_t} = \sqrt{1 + \tan^2 \phi}.$$

The terminal voltage E_t exists, and the reactance voltage E_r exists, and the armature inductance (to which E_r is proportional) causes a retardation in the rise and fall of the alternating current, in accordance with precisely the same laws which would hold for inductance contained in the conducting circuit external to the armature. And also the results of the retardation, so far as relates to the reaction of the armature upon the magnetic field, are in all respects the same as if the inductance were external to the armature, and were not a property of the armature itself. But the one point which must be insisted upon is that (armature C R drop being neglected), there is no so-called internal voltage bearing the relation to the terminal voltage set forth in the expression—

$$\frac{E_i}{E_t} = \sqrt{1 + \tan^2 \phi}.$$

The cyclic curve of terminal voltage, it is true (and that of current also when the external circuit is non-inductive), is retarded in attaining its maximum value with relation to the relative positions in space of conductors and pole-face, by the angle ϕ (whose tangent is $\frac{E_r}{E_t}$) behind the position at which it attained its maximum value when there was no current in the armature, this latter position being that where the conductors stand opposite the middle of the pole-face. Hence, for convenience sake, we may draw the geometrical resultant of

$$E_r \text{ and } E_t, \text{ and call it } E_i \text{ and cos. } \frac{E_t}{E_i} = \phi,$$

the angle of the lag just described. But, in so far as the estimation of the magnitude of the magnetic flux under various conditions is concerned, this flux must be estimated not of such magnitude as to correspond to E_i, but as only sufficient in magnitude to account for E_t. The same result could be arrived at by reasoning that there is

the internal voltage E_i and the corresponding flux, but that a component of that flux is neutralised by the flux corresponding to the reactance voltage E_r leaving a residual flux corresponding in magnitude to E_t; but this is unsatisfactory, inasmuch as this larger flux has no existence in fact.

Experimental Confirmation of the Theory

The above assertion has been experimentally confirmed by tests on alternators of various proportions.

The nature of the results of these will be made clear by the following description of a hypothetical case :—

The alternator has two extra collector rings provided, which constitute terminals of an exploring coil, wound at the bottom of the slots carrying one of the main coils. The voltage at the terminals of the exploring coil is measured when there is no load and 2020 volts on the main winding, and again when there are 200 amperes and 2000 volts on the main winding. The ohmic resistance of the armature winding is 0.1 ohm.

Whereas 4000 ampere turns per pole-piece sufficed to maintain the terminal voltage at 2020 with no load, in the second case there is required a field excitation of 5000 ampere turns per pole-piece to maintain the potential at 2000 volts at the main collector rings with a load of 200 amperes. But in both cases we obtain the same potential at the terminals of the exploring coil; from which it follows that the magnetic flux linked with the main coil is also the same in both cases, *i.e.*, the same at full load as at no load.

The significance of this conclusion lies in the consequence that, to correctly interpret the performance of alternators, we must only take the reactance voltage into account in determining the phase displacement of the terminal voltage E_t from the mid-pole-face position ; and we must disabuse our minds of the impression that the reactance voltage and the terminal voltage combine to make an internal voltage, with which latter there is associated a resultant magnetic flux greater than suffices for the terminal voltage in the ratio $\frac{E_i}{E_t}$.

Thus the field excitation, to maintain the same collector-ring voltage at no load as at full load, need only be increased by an amount corresponding to the demagnetising component of the armature ampere turns,

i.e., by an amount sufficient to maintain through the armature winding the same main flux as at no load.

The authors are of opinion that, even if allowance is made for a reactance voltage component in deriving the true internal flux, great care should be taken in this case to employ only that component of the "apparent" reactance voltage which corresponds to that part of the armature stray flux which does not enter the field pole-face. This is a much smaller flux than that corresponding to the "apparent" reactance voltage; and the vectorial inclusion of the reactance voltage corresponding to this small component flux will lead to a total internal flux and voltage but little greater than the flux corresponding to the terminal voltage. Hence this small component could exist, and still escape detection in the tests described above. These tests are, however, conclusive in negativing the existence of a vector component of the internal voltage of any such magnitude as corresponds to the "apparent" reactance voltage.

In a paper in which one of the authors recently collaborated[1], a method is laid down in which this plan of procedure is followed. For machines with low or moderate saturation of the magnetic circuit, the results obtained by this latter method are in very fair agreement with the results obtained by the method set forth in the present treatise. Where high saturation of the magnetic circuit is employed, the results obtained by the American Institute paper above referred to, are considerably more accurate[2], and it is often preferable in such cases to employ it in the final design, although the very great simplicity of the calculations and diagrams employed in the method set forth in the present treatise permit of a much more comprehensive grasp of the subject in preparing the preliminary designs. In fact, it is the authors' practice to employ the present method very generally, and to make approximate corrections proportionate to the degree of saturation employed. The exigencies of commercial designing generally render simple

[1] "Contribution to the Theory of the Regulation of Alternators," H. M. Hobart and F. Punga, read before the American Institute of Electrical Engineers, New York, April 22nd, 1904.

[2] One other feature to which much attention has been given in the American Institute paper is the influence of the ratio of the pole arc to the pole pitch. This has also been neglected in the present method, as alternators generally vary but slightly in this respect. It need only be mentioned here that a very small value for this ratio considerably improves the regulation for unity power factor, but impairs it slightly for lower power factors.

methods preferable, even when the final results require correction by more elaborate methods. In the present case, however, such correction is only necessary in designs with highly-saturated circuits. In such designs the uncorrected results indicate an inherent regulation inferior to that which will be actually obtained. Hence the error is on the safe side.

It has been necessary to treat this question at considerable length, since on the value of the actual maximum magnetic flux present depends not only a series of conclusions with reference to the saturation of the magnetic circuit under various conditions, and the corresponding necessary excitation, but also all calculations relating to core loss. It is, however, the first group of considerations which will now occupy our attention.

The terms "reactance," "reactance voltage," "angle of lag," "impressed flux," etc., as used in the preceding explanations, may be thought by some not to be the most satisfactory that might have been adopted. It can only be stated that, as nearly as appeared practicable, use has been made of the most approved and widely-adopted conceptions of these terms, while at the same time some very thoroughly experimentally-demonstrated facts had also to be taken into consideration. After a large amount of investigation, the present use of terms was decided upon as best reconciling these two conditions; and the writers are of the opinion that a careful consideration of the examples of the application of these terms to alternator design will lead to a recognition that, from the practical standpoint, they are correct, exact, and useful. Tests will subsequently be described, which will show the experimental curves of alternators to be in close agreement with the curves predetermined on this basis.

Magnetic Leakage (Increase with Load)

In alternators it is customary to make a rough allowance, say from 10 to 15 per cent. up to sometimes 30 or even 40 per cent., for the stray leakage magnetic flux. That is to say, if the magnet cores are long, and with broad sides, and only a few inches apart, and if the air gap is only moderately short, simple approximate calculations of length and cross-section of the various more direct magnetic paths will often show that, of a flux of 130 or 140 kilolines, not over 100 will actually, at no load, cross the air gap to the armature surface, and eventually become linked with the armature winding. In other better cases, with short magnet cores and small air gap, the discrepancy may be as low as 10

per cent. or 15 per cent. There is also a reasonable amount of experimental data constituting an independent basis for such estimates.

When the armature turns carry no current, and hence have no magnetomotive force, there is hardly any fall of magnetic potential from that portion of the surface of the armature where the lines from the north pole enter, to the portion of the surface of the armature where they leave to return to the south pole. But as soon as the armature coils carry current, they become the seat of an independent magnetomotive force, which sets up differences of magnetic potential at the different poles of the armature surface, just as do the field coils at the different poles of the magnetic field. There is one main difference, however; whereas, at a given point of the field, the polarity remains the same, the polarity at a given point of the armature surface changes periodically in response to the alternations in the armature current.

Such changes are in synchronism with the revolutions, and hence this given point on the armature surface will have, at any instant, a given polarity relatively to the pole to which it may be adjacent at such instant. In other words, suppose that this given point on the armature be energised as a pole (N) by the armature current, by the time the armature has moved round till this point faces a field-pole (S) the armature current alternation will have reversed the polarity sign of the point on the armature, and made it into a pole (S) also; hence it follows that, although the point on the armature changes polarity, it always retains the same sign in relation to the pole-face it may be opposite. With 90 degs. lagging current, the armature polarity is of maximum strength when directly opposed to the field polarity. With 90 degs. leading current, the armature polarity is of maximum strength, but in exactly the same direction as the field polarity. When the armature current is in phase (*i.e.*, neither lagging nor leading with relation to the uniformly distributed magnetic field) the armature polarity is at a maximum when its poles are midway between the field-magnet poles, and hence in a position where it can have no effect, either to oppose or aid the field-poles, except to the extent of distorting the flux distribution. But the point here under consideration is not the demagnetising or magnetising effect, but a secondary result, namely, the variations which these effects bring about in the magnetic leakage.

In Fig. 448, on the next page, is shown one magnetic circuit of a multipolar machine.

The field excitation may be assumed to be 5000 ampere turns per pole. Of this magnetomotive force of 5000 ampere turns, 2500 are required to overcome the magnetic reluctance of the field magnet, 1000 for each air gap, and the remaining 500 overcome the magnetic reluctance of the armature part of the circuit A. Between the surfaces *m* and *n*, the difference of magnetic potential is 2500 ampere turns, and between *o* and *p* it is 500 ampere turns.

But suppose, in the position shown in Fig. 448, there flows such a current in the armature coils as to set up a magnetomotive force of

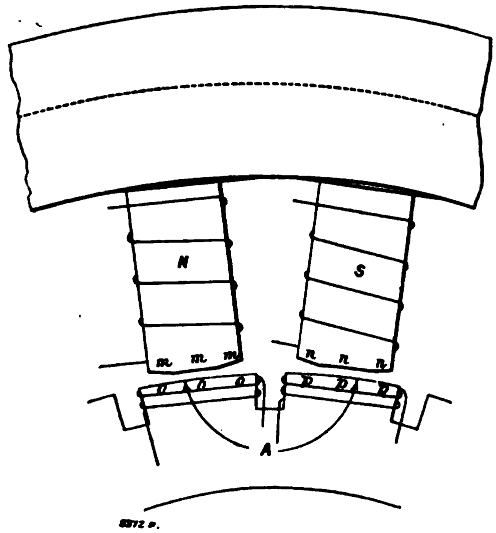


FIG. 448. ONE MAGNETIC CIRCUIT OF MULTIPOLAR ALTERNATING-CURRENT GENERATOR

2000 ampere turns in this same magnetic circuit. In the first place, the current may be supposed to be lagging by 90 deg. Let the field excitation be increased from 5000 to 7000 ampere turns, so as to maintain the same total of magnetic flux in spite of the demagnetising influence of the armature current. The magnetic potential between the points *m* and *n* increases from 2500 to 4500 ampere turns, and that between the points *o* and *p*, from 500 to 2500 ampere turns. Hence, there will be a greatly-increased leakage flux, especially towards the lower ends of the magnet cores, and over the armature surface. Assuming the same value for the armature current, but assuming it to lead by 90 deg. instead of to lag, then the field excitation must be reduced from 5000 to 3000 in order to maintain the same magnetic flux. This reduces the difference

of magnetic potential between points m and n from 2500 to 500 ampere turns, but that between o and p is increased from 500 to 1500; that is to say, of the magnetomotive force of 2000 ampere turns, furnished by the magnetising armature current, 500 are consumed in overcoming the magnetic reluctance of the armature laminations, and 1500 remain available beyond o and p. But as 2000 are necessary for the gaps (1000 for each), the 1500 ampere turns of the magnetomotive force of the armature require 500 of the 3000 supplied by the field coils, to overcome the reluctance of the gap up to the pole-faces m n, leaving 2500 ampere turns as before, to overcome the reluctance of the field magnets.

From Table LXV. it appears that, representing the leakage flux from the region $m\,m\,m$, $o\,o\,o$, to $n\,n\,n$, $p\,p\,p$, at no-load, by $\frac{2500 + 500}{2} = 1500$, then with 90 deg. lag, and an armature strength of 2000 ampere turns, this leakage flux will have increased to $\frac{4500 + 2500}{2} = 3500$, but that with 90 deg. leading current, it decreases to $\frac{500 + 1500}{2} = 1000$. Or, letting 1 represent the leakage flux under the first condition (no-load),

TABLE LXV.—MAGNETIC POTENTIAL BETWEEN SURFACES WITH FLUX F.

—	No-Load.	2000 Armature Ampere Turns.	
		With 90 Deg. Lag.	With 90 Deg. Lead.
m and n	2500	4500	500
o and p	500	2500	1500
Field excitation	5000	7000	3000

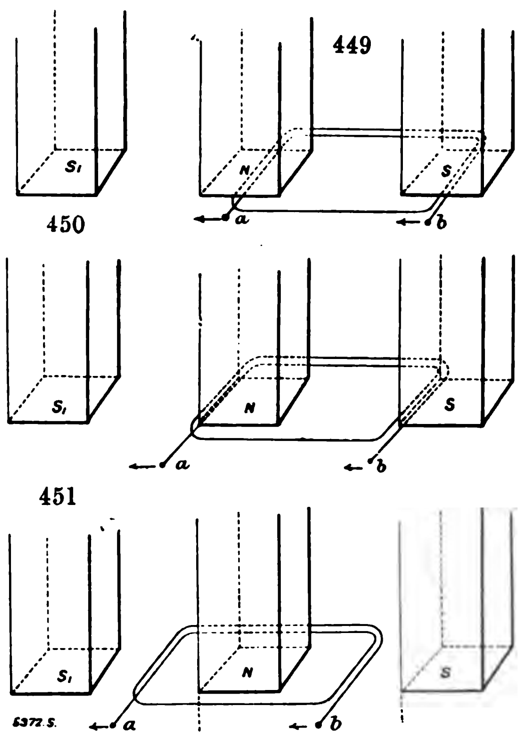
then 2.3 represents the leakage flux for lagging full-load current, and 0.67 for leading full-load current, a very wide range of alteration.

This brief statement makes no pretence to exactness, but is merely intended to emphasise the fact that the leakage coefficient may be considerably affected by the amount and nature of the load. Alternators in which the field excitation is strong, and the armature strength, in ampere turns per pole, weak, are, of course, less subject to this variation. Moreover, in practice, machines rarely carry loads making up a total

power factor of less than 0.85 ; but, even with unity power factor, if the armature winding is very inductive, the armature current will reach its maximum value at a position corresponding to a considerable displacement of the armature polarity beyond the neutral point ; and, as will now be explained, will be effective in opposing the field magnetisation.

Demagnetising Effect of the Armature Current

It may be said that the armature demagnetising effect increases proportionally to the sine of the angle, by which the maximum value



Figs. 449 to 451. Diagrams to Illustrate the Influence of Armature M.M.F.

of the current lags behind the mid-pole-face position, and tests made for the purpose prove this to be approximately the case.

Particular notice should, however, be drawn to the fact that the demagnetisation increases at first very rapidly, as the position of maximum value of the current begins lagging in phase behind the mid-pole-face position, and reaches nearly its full value when the conductors of the armature coils are opposite the pole-corners at the moment of maximum current ; afterwards increasing more slowly.

In Fig. 449, page 419, suppose *a b* to form conductors of a coil on the armature, and N S two pole-faces. The position shown illustrates the case in which the maximum value of the current is reached when the centre of the coil *a b* is exactly midway between the two poles N S, the conductors being exactly at the mid-pole-face position. In this position, therefore, the demagnetising effect of the current in the armature coil *a b* is a minimum.

In Fig. 450, page 419, the maximum value of the current occurs somewhat later, hence this represents the case of a considerable angle of lag. From the position in Fig. 449 up to this point (conductors opposite pole-corners, see dotted line) the demagnetising effect increases very rapidly, but when this position is passed it increases much more slowly.

Fig. 451 shows the position where the current is at a maximum when the centre of the coil *a b* is exactly opposite the pole-face N, the conductors *a b* thus being midway between two poles, S N and N S. In this case the angle of lag is 90 deg. At this position the demagnetising effect of the armature current is greatest; but, as before pointed out, it increases but very little after the conductors *a b* of the coil pass the pole-corner shown by dotted line.

It is convenient and sufficiently accurate to take the demagnetising effect as increasing proportionately to the sine of the angle of lag between the mid-pole-face position and the position of the conductors when carrying maximum current; and this is of importance in predicting the performance of an alternator under various conditions of service.

Predetermination of Characteristic Curves for a 225-Kilowatt Single-Phase Alternator

The method may best be illustrated by applying it to an example. A certain single-phase alternating current generator has a magnetic circuit of such proportions as to require, at no-load and 2250 volts, a field excitation of 3100 ampere turns per field spool.

The machine has 28 poles. It has 14 armature coils of 28 turns each. Therefore, $\frac{14 \times 28}{28} = 14$ turns on armature per pole-piece.

Full load = 225 kilowatts.

Therefore, full-load current = 100 amperes (at 2250 volts).

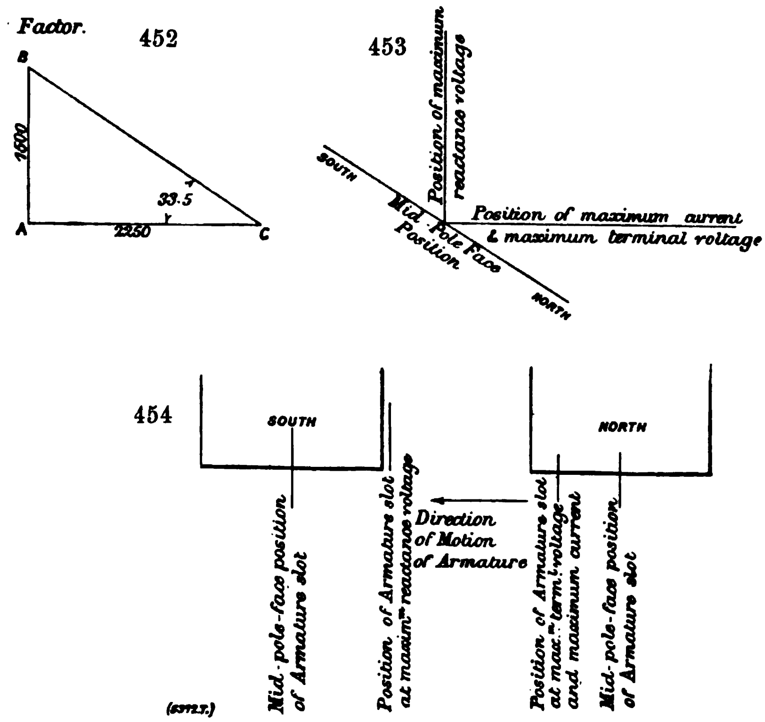
Gross length of armature lamination parallel to shaft = 10.5 in

Average inductance may in this case be taken at 25 C.G.S. lines per ampere turn and per inch gross length of armature laminations.

Inductance of one coil $= 28^2 \times 0.00000025 \times 10.5 = 0.00205$ henry.
Inductance of entire armature (14 coils in series) $= 14 \times 0.00205 = 0.0287$ henry.
Speed of armature = 356 revolutions per minute.

Periodicity $= \dfrac{356 \times 28}{2 \times 60} = 83$ cycles per second.

Reactance $= \pi \times 83 \times 0.0287 = 15.0$ ohms.
Reactance voltage with full-load current of 100 amperes $= 100 \times 15 = 1500$ volts.



FIGS. 452 TO 454. DIAGRAMS FOR UNITY POWER FACTOR

Assuming a sine wave-current curve, there are on the armature, at full-load current,

$$14 \times 100 \times \sqrt{2} = 1980 \text{ ampere turns per pole-piece.}$$

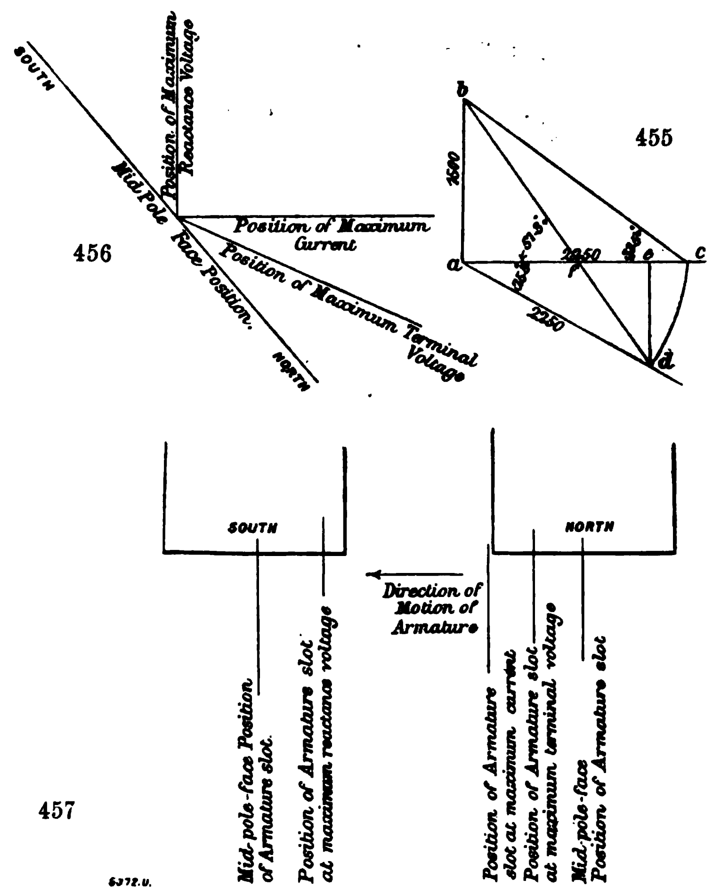
When the external load is non-inductive (see Figs. 452 to 454), the tangent of the angle of lag of the position of maximum current behind the mid-pole-face position

$$= \frac{AB}{AC} = \frac{1500}{2250} = 0.665.$$

Therefore, angle of lag = 33.5 deg.;
And sine of angle of lag = 0.552 deg.

Hence, demagnetising effect of armature under these conditions (*i.e.*, non-inductive full-load beyond collector rings) = 0.552 × 1980 = 1100 ampere turns.

Therefore, field excitation required with full load (externally non-inductive) = 3100 + 1100 = 4200 ampere turns per field spool.[1]



FIGS. 455 TO 457. DIAGRAMS FOR POWER FACTOR 0.90

Furthermore, the method admits of the predetermination of the necessary field excitation for any load in amperes, and for any power-factor. Thus, in the machine under consideration, determination may be made as follows, of a curve showing the necessary excitation for maintaining the terminal voltage constant at 2250, when full-load current of 100 amperes is furnished, the power-factor of the external

[1] The armature C R drop is not considered in any of these calculations and diagrams, as the error thereby introduced is negligible.

load varying from 1.00 down to very small values. The requisite excitation for an external load having a power-factor of 1.00 has already been found to be 4200 ampere turns per field spool.

For power-factor of 0.90 in the external circuit (see Figs. 455 to 457), proceed as follows :—

In Fig. 455 lay off the angle $d\,a\,c$ = 25.5 deg. (cos. 25.5 deg. = .90) as shown.

Angle $a\,b\,c$ has already been found to be 33.5 deg.

Angle $a\,f\,b = \tan^{-1}\frac{a\,b}{a\,f} = \tan^{-1}\frac{1500}{1200} = \tan^{-1}1.25 = 51.3$ deg. = total angle of lag between mid-pole-face position and position of maximum current.

Therefore, sine $a\,f\,b = 0.780$.

And ampere turns per field spool = 3100 × (0.780 × 1980) = 3100 + 1550 = 4650 ampere turns.

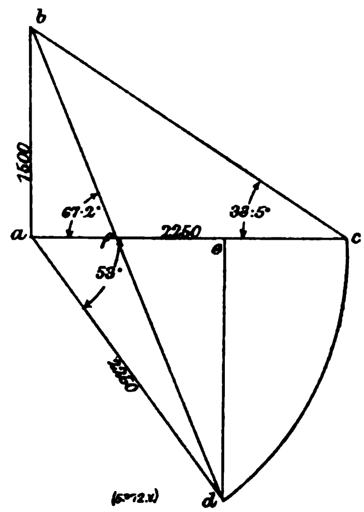


FIG. 458. DIAGRAM FOR POWER FACTOR OF 0.60

Thus it appears that, in the case of this particular machine, a power-factor of 0.90 for the external load demands an increase of 11 per cent. in the excitation over that required for a non-inductive external load of the same amperage. Next, with a power-factor of 0.60 for the external load, construct Fig. 458, in which angle

$$d\,a\,c = 53.0 \text{ deg.} = \cos.^{-1}0.60.$$

This gives

$$a\,f\,b = \tan^{-1}\frac{1500}{630} = \tan^{-1}2.38 = 67.20 \text{ deg.}$$

$$\text{Sine } 67.2 \text{ deg.} = 0.922$$

$$1930 \times 0.922 = 1830$$

$$1830 + 3100 = 4930$$

Therefore, 4930 = ampere turns necessary for 2250 terminal volts when power-factor of external load = 0.60.

Lastly, as the power-factor approaches zero (90 deg.), the armature demagnetisation will approach 1980 (maximum ampere turns per pole-piece on armature). Therefore, in this case, the field excitation for 2250 terminal volts and full-load current (100 amperes) = 1980 + 3100 = 5080 ampere turns.[1]

The above results are, for convenience, summarised in Table LXVI.:—

TABLE LXVI.

Power factor of external load...	1.00	0.90	0.60	0.0
External angle of lag (*i.e.*, angle of lag of maximum value of current behind maximum value of terminal voltage)... ... ... deg.	0.0	25.5	53.0	90.0
Internal angle of lag (*i.e.*, angle of lag of maximum value of terminal voltage behind mid-pole-face position) ... ... deg.	33.5	33.5	33.5	33.5
Resultant angle of lag (*i.e.*, angle of lag of maximum value of current behind mid-pole-face position deg.	33.5	51.3	67.2	90.0
Excitation per field spool for 2250 terminal volts and 100 amperes	4200	4650	4930	5080

Fig. 459 gives a curve showing the necessary excitation for 2250 volts and 100 amperes, with various power-factors.

LOAD SATURATION CURVES

It is proposed to next calculate the saturation curve at full (externally non-inductive) load of 100 amperes.

(1) Terminal voltage = 0. Excitation per field spool will be slightly in excess of maximum ampere turns per pole-piece on armature. Therefore, field excitation = 1980 ampere turns per spool.

(2) Terminal voltage = 400. The saturation curve of this machine at no-load is a straight line up to 2250 volts; see Fig. 461, page 426.

[1] In reality, the line *a b* ought to have been shortened with each increase of lag of the current, as the current reaches its maximum value when the slot is nearer the position of minimum inductance, as already pointed out. Hence, in practice, the necessary ampere turns per field spool should not increase so much, with decreased power factor of the external load, as the results of this calculation show.

Then $\frac{400}{2250} \times 3100 = 550$ ampere turns per field spool. And to obtain armature demagnetisation by foregoing method (Fig. 460, page 426):

Angle of lag of current behind the mid-pole-face position

$$= \phi = \tan^{-1}\frac{1500}{400} = \tan^{-1} 3.75 = 75.1 \text{ deg.}$$

Therefore

$$\text{sine } \phi = 0.966.$$

And $0.966 \times 1980 = 1910$ ampere turns armature demagnetisation. Hence $550 + 1910 = 2460$ ampere-turns per field spool for 400 terminal volts, and 100 amperes with non-inductive load.

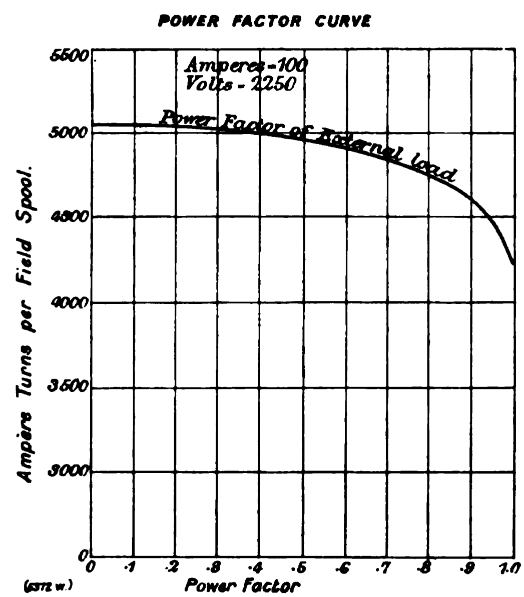


FIG. 459. CURVE OF EXCITATION FOR VARIOUS POWER FACTORS

Following this method, calculations are made for 1000 and 2000 volts, and all the results incorporated in Table LXVII., and illustrated by the curves of Fig. 461, page 426.

TABLE LXVII.

Amperes in armature	100	100	100	100	100
Voltage at armature terminals	0	400	1000	2000	2250
Ampere turns per field spool	1980	2460	3010	3945	4200

Here again, while the first point and the last point would be

almost correct, the intermediate points, especially that at 400 volts, would be very inaccurate through taking the *average* inductance as a basis for the line *a b*. As a matter of fact, it would be very near the minimum inductance, and the angle ϕ is very dependent at this point on the length of *a b* as compared with *a c*. If corrected, the curve would more resemble the dotted line shown in Fig. 461, in which the full line gives the

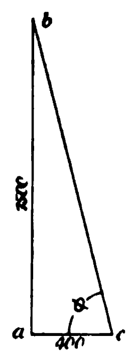


Fig. 460.

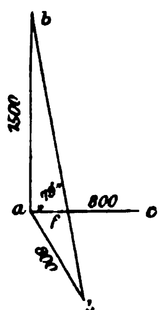


Fig. 462.

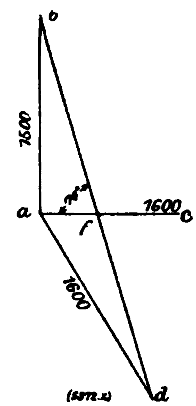


Fig. 463.

Vector Diagrams of Alternator Regulation

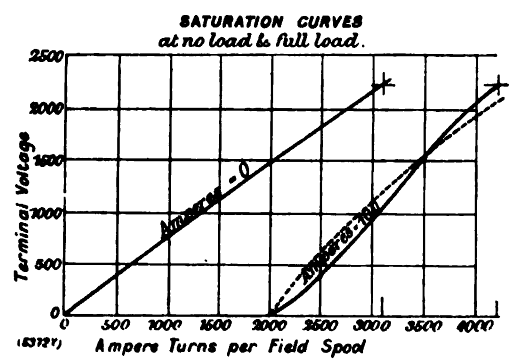


Fig. 461.

uncorrected calculated curve of ampere turns per field spool for various voltages, with non-inductive external load. When the external load is inductive, the saturation curve for a given current (say, full-load current of 100 amperes) differs from the load saturation curve of Fig. 461; and, in fact, there is a different curve for each value of the power factor of the external load. We have already derived the curve for 100 amperes and unity power factor, and have plotted it in Fig. 461.

Calculation of Saturation Curves for Various Power Factors

1. Power factor = 0.

For terminal voltage = 0, we have already determined that 2000 ampere turns per field spool are required for 100 amperes in the armature.

For terminal voltage = 400. The full armature strength of 1980 ampere turns exerts an effective magnetomotive force in opposition to the field excitation. Consequently we require

$$\frac{400}{2250} \times 3100 + 1980 = 550 + 1980 = 2530 \text{ ampere turns.}$$

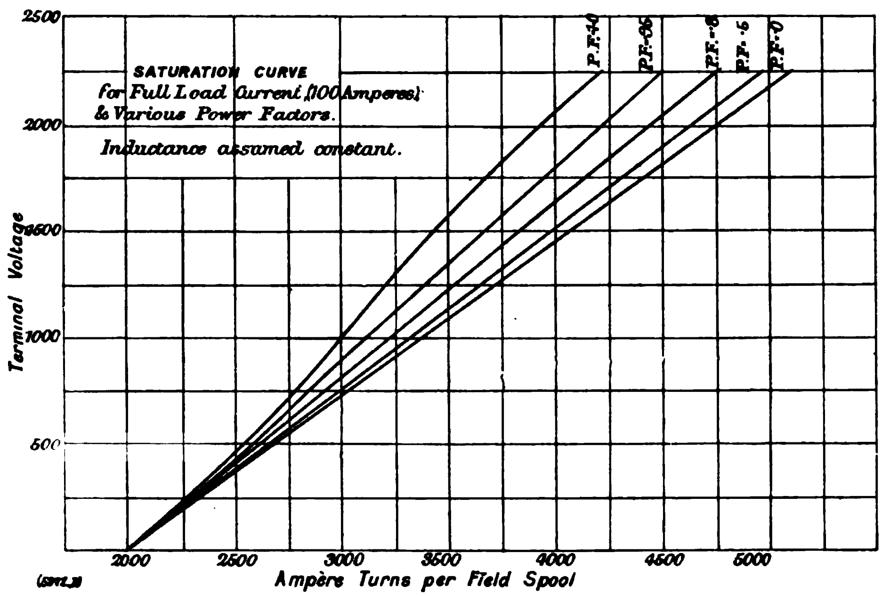


Fig. 464.

For 800 terminal volts:

$$\frac{800}{2250} \times 3100 + 1980 = 3080 \text{ ampere turns.}$$

And so the curve will keep on in a straight line, and at 2250 terminal volts it will reach the value of 5080 ampere turns, already determined in the power-factor curve of Fig. 459, page 425.

2. Power factor = 0.5.

The curve starts, of course, from the same value of 2000 ampere turns at zero terminal voltage.

Terminal voltage = 800. Construct Fig. 462 with ab = 1500, ad = ac = 800. Sin afb = 0.98. Hence the curve continues to this point substantially the same as the curve for power factor = 0.

Terminal voltage = 1600. Construct Fig. 463, where $a\,d$ has become 1600.

$$\text{Sin } a f b = 0.96.$$

$$\text{Field excitation} = \frac{1600}{2250} \times 3100 + 0.96 \times 1980 = 2200 + 1900 = 4100.$$

At terminal voltage of 2250 the excitation will be 4975 ampere turns per field spool, as shown by the power factor curves of Fig. 459. The results for similar calculations at power factors of 0.8 and 0.95 are arranged with the preceding in the following Table, and are plotted in the curves of Fig. 464.

TABLE LXVIII.—FIELD EXCITATION WITH 100 ARMATURE AMPERES AND VARIOUS POWER FACTORS (INDUCTANCE ASSUMED CONSTANT)

Terminal Voltage.	Power Factor.				
	0	0.5	0.8	0.95	1.0
0	2000	2000	2000	2000	2000
800	3100	3050	2980	2910	2840
1600	4200	4100	3950	3770	3500
2250	5080	4975	4760	4500	4200

CALCULATION OF CURVES OF EXCITATION REGULATION

First case: Non-inductive external load. (Power factor = 1.00.)

To obtain the curve of excitation regulation, showing ampere turns per field spool required for 2250 terminal volts at all currents from no load to full load, and with non-inductive external load, proceed thus:—

First: Amperes = 0. There are required (see no-load saturation curve of Fig. 461, page 426) 3100 ampere turns per field spool.

Second:

$$\text{Amperes} = 33. \quad \text{Reactance voltage} = \frac{33}{100} \times 1500 = 500 \text{ volts.}$$

$$\text{Angle of lag} = \tan^{-1}\frac{500}{2250} = \tan^{-1} 0.222 = 12.5 \text{ deg.}$$

$$\text{Sin } 12.5 \text{ deg.} = 0.217. \quad 0.217 \times \frac{33}{100} \times 1980 = 142.$$

Hence, 142 + 3100 = 3242 ampere turns per field spool for 33 amperes and 2250 terminal volts.

Similarly, the remaining values in the following Table are obtained:

TABLE LXIX.—EXCITATION FOR VARIOUS LOADS AT UNITY POWER FACTOR AND 2250 TERMINAL VOLTS

Volts at terminals	2250	2250	2250	2550
Amperes in armature	0	33	67	100
Ampere turns per field spool ...	3100	3242	3640	4200

And these values are plotted in the lower curve of Fig. 466.

Second case: External load with power factor = 0.08.

For zero amperes, 3100 ampere turns are, of course, required as

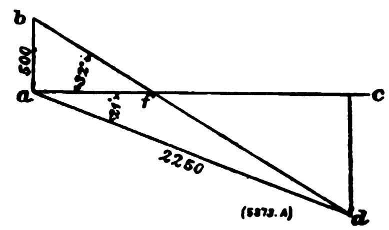


FIG. 465. EXCITATION REGULATION

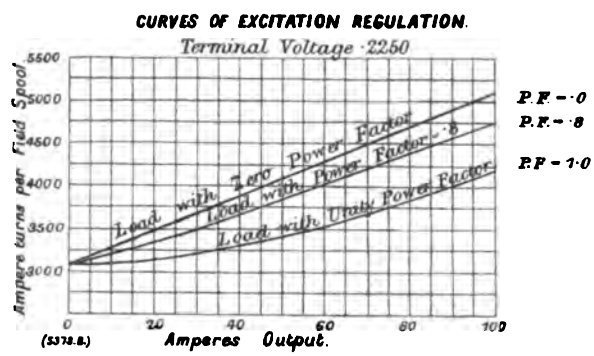


FIG. 466.

before. For 33 amperes, reactance voltage = 500 volts. Construct Fig. 465, with

$ab = 500$, $ad = 2250$, and angle $dac = 37$ deg. (cos. 37 deg. = 0.8).

Then angle $afb = 45.8$ deg. Sin 45.8 deg. = 0.716.

$$0.716 \times \frac{33}{100} \times 1980 = 465.$$

465 + 3100 = 3565 = excitation required for 2250 terminal volts when the alternator delivers 33 amperes to an external circuit with a power factor of 0.8. The remaining values in the following Table are similarly calculated:

TABLE LXX.—EXCITATION FOR VARIOUS GOODS AT 0.80 POWER FACTOR AND 2250 TERMINAL VOLTS

Volts at terminals	2250	2250	2250	2250
Amperes in armature	0	33	67	100
Ampere turns per field spool ...	3100	3565	4155	4760

These values are plotted in the middle curve of Fig. 466.

Third case: External circuit with power factor = 0.

In this case the full armature strength is exerted in opposition to the field excitation, which latter must, therefore, receive increments in direct proportion to the armature amperes, in order to maintain the terminal voltage constant at 2250 volts for all values of the amperes output. Hence the curve of excitation regulation for power factor = 0

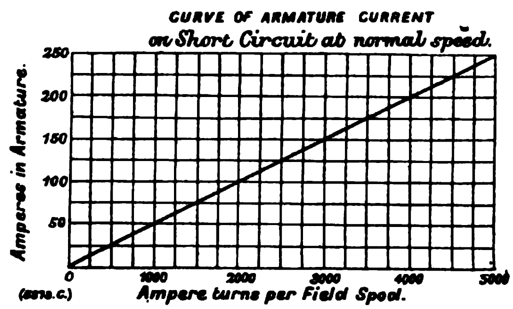


FIG. 467.

must be a straight line connecting 3100 ampere turns (the excitation for zero amperes output), with 5080 ampere turns (the value for 100 amperes output already found for the curve of Fig. 464, page 427). This is shown in the upper curve of Fig. 466.

THE "SHORT-CIRCUIT" CURVE

The "short-circuit" curve is a curve plotted with field excitation as abscissæ, and with armature currents on short circuit as ordinates, the alternator being driven at its normal speed. The current reaches its maximum value when the slot is 90 deg. behind the mid-pole-face position (*i.e.*, the angle of lag is 90 deg.). Hence the full armature strength is exerted in direct opposition to the field spool magnetomotive force, and the field excitation requires to be of such a value as to suffice to overcome the small C R drop in the armature conductors. Therefore,

the ampere turns per field spool will for each value of the armature current, be just about equal to the maximum value of the armature ampere turns per pole-piece. The curve will be a straight line passing through the origin, and through the point having 100 amperes for its ordinate and 1980 ampere turns for its abscissæ, this being the maximum armature ampere-turns per pole-piece at full-load current of 100 amperes. The curve is given in Fig. 467.

Calculation of the Volt-Ampere Curve

The volt-ampere curve is taken with constant field excitation, and is plotted with ordinates representing the terminal voltage, and abscissæ representing the amperes output. The curve is a function of the power factor of the load.

Volt-Ampere Curve for Power Factor = 1

For the greatest accuracy, the calculation of the volt-ampere curve requires a knowledge of the inductance of the armature winding for all positions, from the mid-pole-face position to the position of minimum inductance. Generally, however, one obtains a curve amply satisfactory for practical purposes by taking at all positions the *average* value of the inductance. We shall now proceed to make the calculation for the alternator, using the *maximum* value of the reactance (18 ohms) for all current outputs from zero amperes up to 75 amperes (75 per cent. of full-load current), the *average* value (15 ohms) from 75 amperes up to about 150 amperes, and the *minimum* value (12 ohms) from 150 amperes up to the current at short circuit.

The no-load saturation curve Fig. 468, page 432, which differs from that of Fig. 461 only in being carried up to high saturation values, is used in the calculations.

It has already been found (see Fig. 459, page 425), that 4200 ampere turns are required for 2250 volts with full non-inductive load of 100 amperes. So the volt-ampere curve will be calculated with a constant field excitation of 4200 ampere turns.

For zero amperes output we find from the saturation curve of Fig. 468 that we shall have 2900 volts.

For 40 amperes: Reactance = 18 ohms. Reactance voltage = 720.

The problem is to obtain the corresponding terminal voltage : Let terminal voltage = x. Then tangent of angle of lag of position of maximum current behind mid-pole-face position $= \frac{720}{x}$.

Full armature strength, with 40 amperes, is

$$\frac{40}{100} \times 1980 = 790 \text{ ampere turns.}$$

The demagnetising component of these 790 ampere turns is equal to

$$\sin\left(\tan^{-1}\frac{720}{x}\right) \times 790.$$

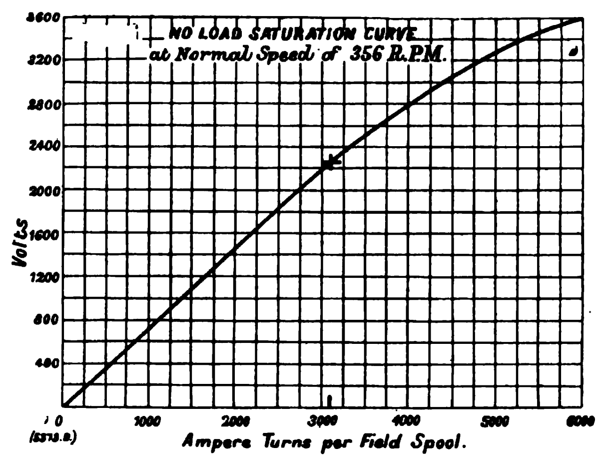


FIG. 468.

Hence the residual ampere turns are equal to

$$4200 - \sin\left(\tan^{-1}\frac{720}{x}\right) \times 790. \quad . \quad \text{(A.)}$$

And in Fig. 468, the ordinate corresponding to this abscissa must equal the volts x. The quickest practical method is to substitute trial values for x in the term (A) until the correct value is found, thus:

Try x = 2500 volts.

$$\begin{aligned}
&4200 - \sin\left(\tan^{-1}\frac{720}{2500}\right) \times 790 = \\
&4200 - \sin(\tan^{-1} 0.29) \times 790 = \\
&4200 - \sin 16 \text{ deg.} \times 790 = \\
&4200 - 0.28 \times 790 = \\
&4200 - 221 = \\
&3979 \text{ ampere turns.}
\end{aligned}$$

This corresponds (see saturation curve of Fig. 468) to 2780 volts. Hence the assumed value was too low.

Hence try $x = 2800$ volts.

$$4200 - \sin\left(\tan^{-1}\frac{720}{2800}\right) \times 790.$$
$$4200 - \sin(\tan^{-1} 0.257) \times 790.$$
$$4200 - 0.25 \times 790.$$
$$4200 - 198 \times 198.$$
$$4002 \text{ ampere turns.}$$

This corresponds to 2800 volts. Hence $x = 2800$ volts.

Similar calculations for other points give values from which the full line curve of Fig. 469 is plotted. If the *average* value for the

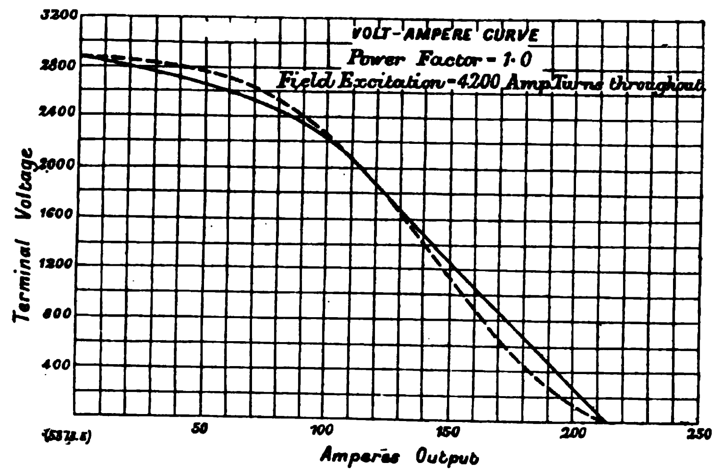


FIG. 469. VOLT-AMPERE CURVES

reactance (15 ohms) had been taken throughout the whole range of the curve, the shape would have been altered, as shown by the dotted curve of Fig. 469. Of course, the full line is the more correct curve, and will more nearly check the experimental curve. But the saving in time secured by the use of the average value throughout is justified in the majority of cases where there is occasion to calculate such curves.

The upper portion of the volt-ampere curve, *i.e.*, the portion representing the range from no-load to full-rated load, gives the curve of inherent regulation. This *should* often be calculated with considerable care; but throughout its range, with most alternators, the current, for unity power factor, reaches its maximum value with a sufficiently small angle of lag behind mid-pole-face position to correspond to the condition of maximum reactance; and for non-inductive loads the maximum value

of the reactance should generally be taken in calculating the curve of inherent regulation.

Volt-Ampere Curve for Power Factor = 0

As the angle of lag is now 90 deg., the armature current is always fully demagnetising, its magnetomotive force increasing in direct proportion to the current. Hence, but for magnetic saturation, the volt-ampere curve would be a straight line. Excitation required for 2250 terminal volts with 100 amperes and zero power factor = 5080 (see Fig. 459, page 425). Hence the field excitation per spool is maintained constant at 5080 ampere turns throughout the curve. From the no-load saturation curve of Fig. 468, the voltage for zero amperes output is found to be 3320 volts.

At 50 amperes output, the armature magnetomotive force $= \frac{50}{100} \times 1980 = 990$ ampere turns. Hence, resultant magnetomotive force $= 5080 - 990 = 4090$ ampere turns, and from the saturation curve the corresponding voltage is found to be 2800 volts.

At 100 amperes output we already know the voltage, with 5080 ampere turns of field excitation, to be 2250 volts. Below 2250 volts, the saturation curve for this alternator is a straight line; hence it only remains to locate the armature amperes at short circuit, with 5080 ampere turns per field spool. Fig. 467 shows this to be 255 amperes. Hence the following quantities, from which the upper curve of Fig. 470 is plotted:—

Amperes Output at Zero Power Factor.	Corresponding Terminal Voltage when Field Excitation per Spool Equals 5080 Ampere Turns.
0	3320
50	2840
100	2250
255	0

It is evident that this volt ampere curve for zero power factor is independent of the armature inductance, hence of any assumption as to its magnitude. But, as a matter of fact, the minimum value of the reactance corresponds to the conditions of the curve, since the slot, at the instants when the current has its maximum value, lies 90 deg. behind the mid-pole-face position. The full line volt-ampere curve for unity power factor has, in Fig. 470, been reproduced from Fig. 469

to facilitate comparison with the volt-ampere curve for zero power factor. Curves for other power factors could be similarly calculated, and would be found to lie in intermediate positions. But it is instructive to show, for the same field excitation in both cases, the volt-ampere curves for

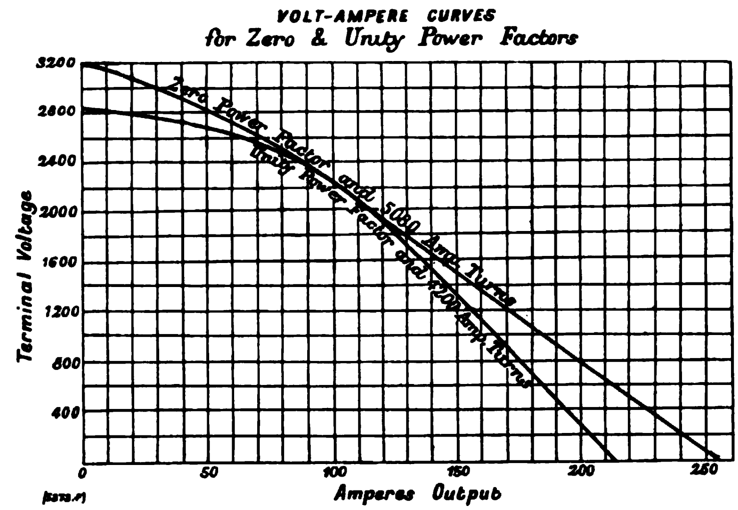


FIG. 470.

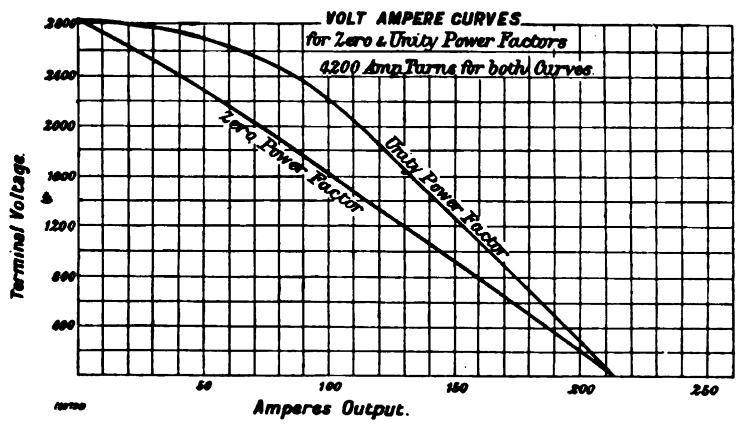


FIG. 471.

VOLT-AMPERE CURVES

zero and unity power factors; and this is done in the two curves of Fig. 471, where the field excitation per spool is 4200 ampere turns.

In Fig. 472, a series of volt-ampere curves for unity power factor, but at different field excitations, is plotted. The *average* value of the inductance has been taken throughout. By decreasing the inductance to the minimum value at the lower end of the curves, the second bend would have disappeared. This would have been more accurate.

Characteristic Output Curve

This is nothing more than a transformation of the volt-ampere curve for unity power factor, but for certain purposes it throws the

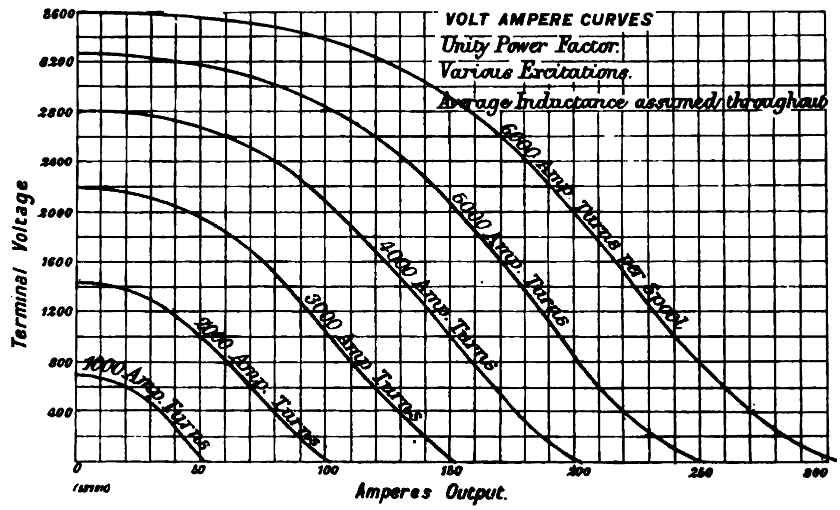


Fig. 472. Volt-Ampere Curves

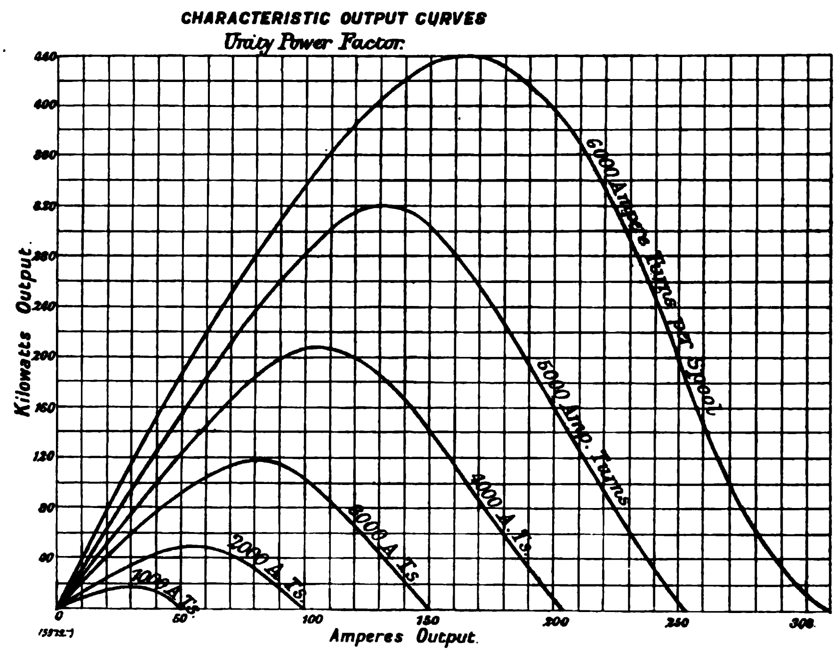


Fig. 473. Characteristic Output Curves

results into a more useful form. In Fig. 473 the volt-ampere curves of Fig. 472 are thus transformed into output curves.

Similar characteristic output curves may be constructed for other

power factors, but the work is tedious, and the curves of Fig. 473 possess the greater interest.

APPLICATION OF THE METHOD TO A SMALL EXPERIMENTAL ALTERNATOR

Having now set forth the leading features of the method, it is proposed to apply it to an actual case, and to show how the theoretical

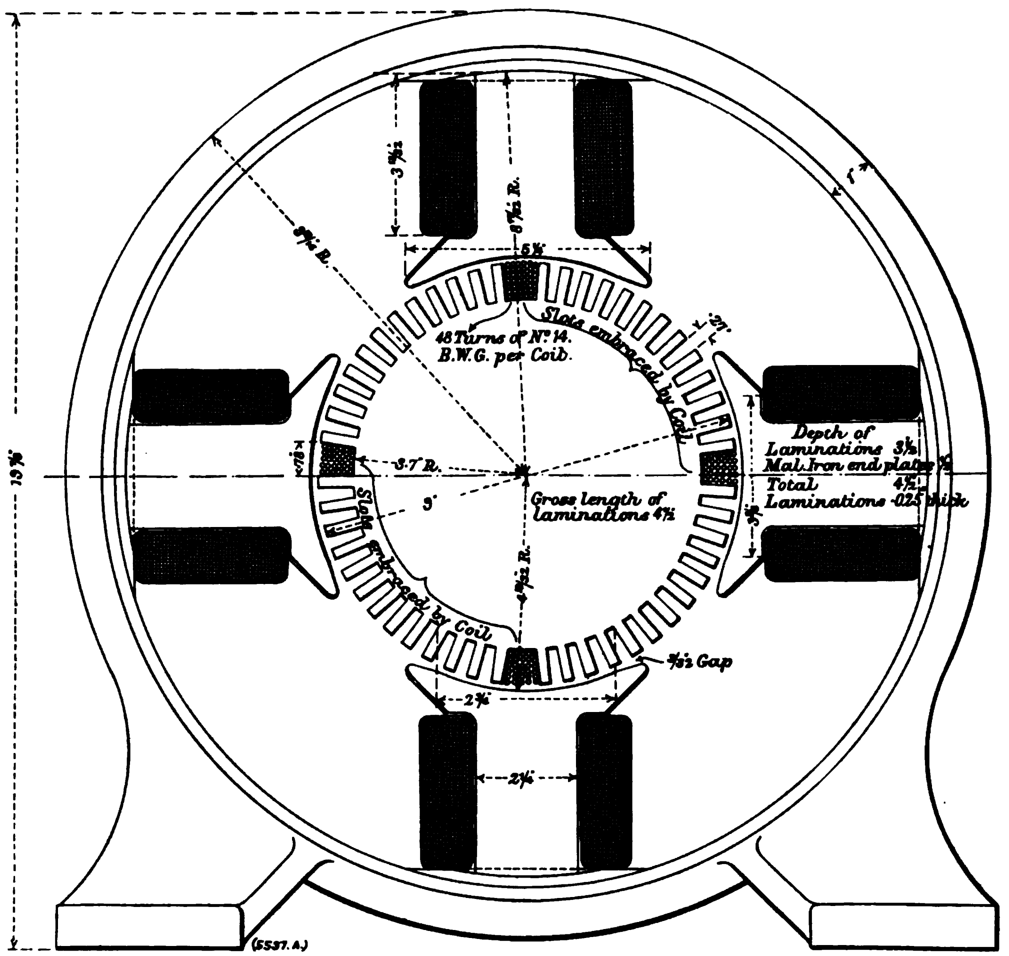


FIG. 474.

MAGNETIC DIMENSIONS OF EXPERIMENTAL ALTERNATOR; 60 VOLTS, 20 AMPERES, 25 CYCLES

and test results compare. For this purpose a small 4-pole continuous-current machine, which happened to be available, was transformed into a uni-slot single-phase alternator, by cutting out four large slots and winding in them two coils of 48 turns each of No. 14 B.W.G. Fig. 474 gives a diagrammatic sketch of the machine.

The theory has been repeatedly tested, in various respects, on large

commercial machines, and the results of such tests will be examined and commented upon in subsequent pages of this treatise. But the small machine at present under consideration has some interesting properties, the study of which will be instructive, and will illustrate the application of the theory to a case where the armature C R drop is a very considerable factor, and must enter into the calculations. Saturation also plays an important part.

The calculated and experimental curves have been carried to points sometimes from two and a-half to three times the normal output; and this, and the abnormal proportions of the machine, should be kept carefully in mind when comparing the values obtained by calculation with the experimentally observed values—as it would be, perhaps, too much to expect closer accordance under these extreme conditions. Entirely aside from the question of confirming the theory set forth in the preceding pages, a description of these tests brings out clearly some very interesting properties of alternating-current generators.

As a matter of fact, the writers have themselves not been entirely satisfied at the outcome of the tests on this small machine, so far as relates to supporting their theory. But they have nevertheless found the results so instructive, for the reasons set forth above, that they have adhered to their original purpose of including the tests in the present treatise. In the meantime, they have pushed forward tests on normally proportioned machines of large capacities, and are obtaining results in every way as satisfactory as the preliminary examinations made during the last few years, all of which pointed very convincingly to the theory now put forth in fairly complete form.

The employment of a small machine, moreover, made it practicable, at slight expense, to arrange loads of various power factors and amounts, up to values far in excess of what would constitute a fair normal rating, and to thoroughly investigate the performance of the machine from all standpoints. The alternator was given a rating of 20 amperes at 60 terminal volts, and at a speed of 750 revolutions per minute, which corresponds to a periodicity of 25 cycles per second.

There will first be given an estimate of the theoretical values of the curves; the test results will follow, and will be set forth in such form as to facilitate comparison.

The saturation curve could have been predetermined, by the well-known methods, but this does not concern the present theory; hence

the experimental values, as set forth in the curve of Fig. 475, are taken as a basis for the calculation.

The inductance was also experimentally determined. In Fig. 476 is given a curve in which the ordinates show the values of the reactance between collector rings, and the abscissæ the corresponding positions of the centre of the slot with respect to the pole-face. The curve shows that, in the position of maximum inductance (*i.e.*, with the centre of the slot opposite the centre of the pole-face), the reactance is (at 25 cycles) 2.4 ohms. In the position of minimum inductance it is but 1.4 ohms.

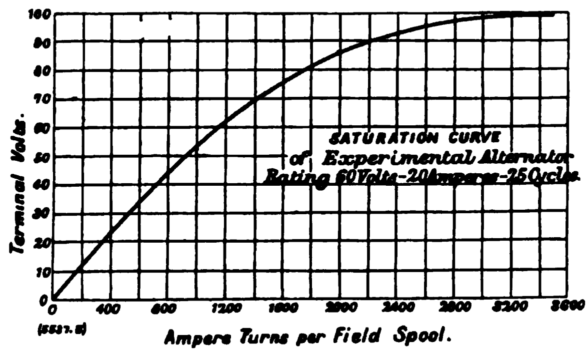


FIG. 475. SATURATION CURVE

From the maximum value of the reactance (2.4 ohms) the corresponding value of the inductance is found to be 0.0153 henry, since

$$l = \frac{2.4}{6.28 \times 25} = 0.0153.$$

Applying the dimensions given in Fig. 474 (gross length armature laminations = 4.5 in.), there is found to be 74 lines per ampere turn and per inch length of armature lamination.

$$\text{Lines} = \frac{0.0153 \times 10^8}{2 \times 48^2 \times 4.5} = \frac{1530000}{2 \times 2300 \times 4.5} = 74.$$

This very high value is attributable to the abnormal dimensions of the machine.

An examination of Fig. 474 will show that the coil is of approximately square cross-section, that the air gap is but $\frac{3}{32}$ in. deep, and that the pole arc is very broad (almost seven times the width of the slot). All these, together with the fact that the embedded portion of the armature winding is but 32 per cent. of the whole armature winding (the exposed end connections constituting the remaining 68 per

cent.) conspire to result in this high value for the inductance when expressed in terms of the magnetic lines per ampere turn and per inch length of armature lamination. The value for the position of minimum inductance is $\frac{1.4}{2.4} \times 74 = 43$ lines.

In large machines of the customary proportions, it has already been shown that the values seldom reach such high figures.

The ohmic resistance of the winding, between collector rings, is 0.31 ohm, which is sufficiently high to materially affect the results, and hence it has been taken into account. In the preliminary descriptions this would have diverted attention from the more important points of the

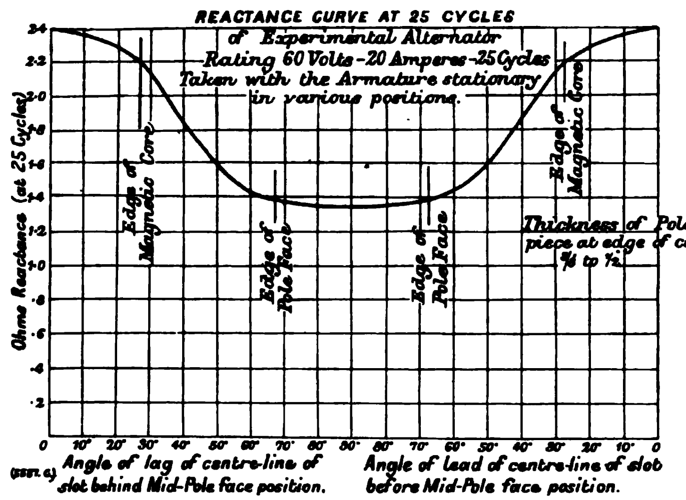


FIG. 476. REACTANCE CURVE

method, but it is now just as well that the effect upon the diagrams of taking the internal resistance into account should be explained. But it must be remembered that—in well-proportioned machines for lighting and power at constant potential—the resistance is practically negligible, and is never accompanied by an armature C R drop of any such percentage of the terminal voltage as is the case in this small experimental machine.

CURVES OF EXCITATION REGULATION

First case: Unity power factor. When the amperes output equals 0, the ampere turns per field spool are found from the no-load saturation curve of Fig. 475 to be 1140 for 60 terminal volts.

Amperes output = 10. In Fig. 477 the line A C represents the terminal voltage of 60 volts. Not knowing in advance of a preliminary calculation the angle of lag of the maximum value of the current behind mid-pole-face position, we make a preliminary assumption of 20 deg., and, from Fig. 476, find the reactance at this position to be 2.28 ohms.

Therefore, the reactance voltage is $2.28 \times 10 = 22.8$ volts.

This is represented in Fig. 477 by A B. The internal drop of voltage is 10 (the current) times 0.31 (the resistance of the winding), or 3.1 volts. This is represented by E B. $\frac{\mathrm{B\,A}}{\mathrm{E\,B} + \mathrm{A\,C}} = \frac{22.8}{63.1} = 0.361$ = tangent of the angle of lag of the current behind the mid-pole-face position = $\tan \phi$ $\therefore \phi = 19.8$ deg.

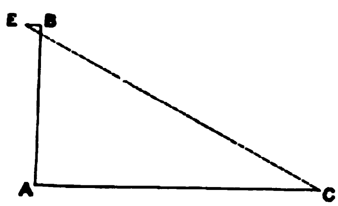


Fig. 477.

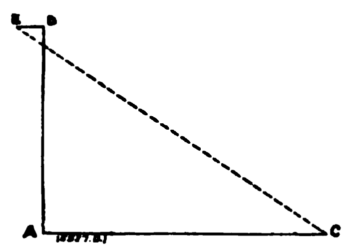


Fig. 478.

Vector Diagrams for Experimental Alternator

This corresponds so nearly to our assumed value (20 deg.) that no re-calculation is necessary.

The full armature strength, expressed in ampere turns per pole-piece upon the armature, $= 24 \times 10 \times \sqrt{2} = 340$ ampere turns.

The demagnetising component $= 340 \times \sin 20 \text{ deg.} \times 340 \times 0.34 = 116$ ampere turns.

The magnetomotive force required for the magnetic saturation is, at 63.1 volts, 1225 ampere turns. Hence the total excitation required for 60 terminal volts and 10 amperes, and unity power factor, is $1225 + 116 = 1341$ ampere turns. By a similar calculation, the value for 20 amperes (full-rated load) is determined to be 1680 ampere turns; and the diagram for this case is given in Fig. 478. The total 1680 ampere turns are made up of 1310 ampere turns for saturation (corresponding 66.2 volts), and 370 ampere turns to offset demagnetisation, this being 0.54 of the total armature strength of $24 \times 20 \times \sqrt{2} = 680$ armature ampere turns per pole-piece.

In the same way the values for higher currents have been calculated, they are set forth in the following figures, and are plotted in the lower full-line curve of Fig. 479, which also gives, in the lower dotted line curve, the experimentally-observed values for unity power factor.

Amperes Output at Unity Power Factor.	Required Ampere Turns per Field Spool for 60 Terminal Volts.
0	1140
10	1340
20	1670
30	2110
40	2420
50	2830
60	3250

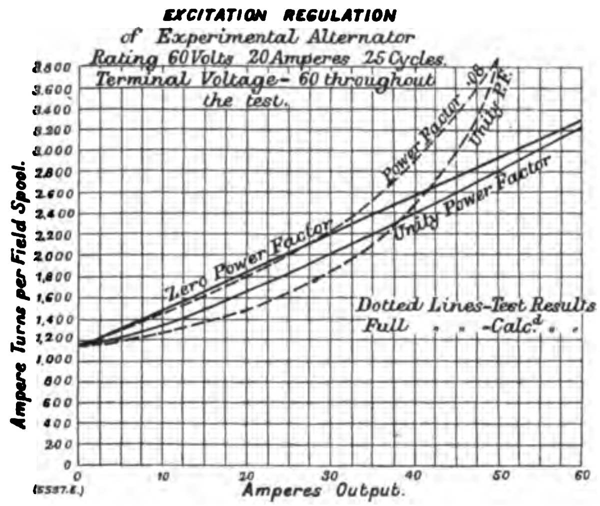


FIG. 479. CURVES OF EXCITATION REGULATION

The calculation for external loads with power factors of less than unity is accomplished as follows :—First case :

Power factor = 0.5
Terminal voltage = 60
Ampere output = 20

Now, for such a case, one may represent the circuit as in Fig. 480, where a resistanceless armature lies between the points A and B, a resistance of 0.31 ohm (the true resistance of the armature) between B and E, the resistance component of the load between A and C, and the reactance component between C and D. As the power factor of the external load equals 0.5, and as the terminal voltage equals 60, we have A D = 60.

$$AC = AD \cos\phi = 60 = 0.5 = 30$$
$$CD = \sqrt{AD^2 - AC^2} = 52,$$

For a trial value we estimate that the angle of lag behind the mid-pole-face position will be 66 deg., in which case the reactance of the armature winding will be 1.4 ohms, and its reactance voltage at 20 amperes will equal 28 volts. So A B is made equal to 28. B E equals 6.2 volts, the resistance drop in the armature at 20 amperes.

$$\text{Then tangent } \phi = \frac{28 + 52}{6.2 + 30} = \frac{80}{36} = 2.22.$$

Hence, ϕ = 65.8 deg., a value which checks the trial value (66 deg.) sufficiently well.

Armature strength = $20 \times 24 \times \sqrt{2}$ = 680 ampere turns per pole-piece.

$$\text{Sin 66 deg.} = 0.91.$$

Hence, demagnetising component = $0.91 \times 680 = 620$. The internal voltage is

$$\sqrt{(\mathrm{E\,B} + \mathrm{A\,C})^2 + \mathrm{C\,D}^2} = \sqrt{36.2^2 + 52^2} = 63.4 \text{ volts};$$

for which are required 1230 saturation ampere turns. Total magneto motive force = 1230 + 620 = 1850 ampere turns per field spool.

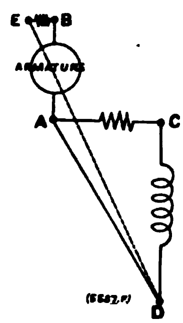


Fig. 480.

In the same way the values given in the following Table were obtained for other loads and for power factor = 0.5, and for various loads and still other power factors.

Table LXXI.—Required Ampere Turns per Field Spool for 60 Terminal Volts and External Loads with the Following Power Factors

Ampere Output.	0	0.3	0.5	0.9	1.0
0	1140	1140	1140	1140	1140
10	1480	1480	1480	1420	1340
20	1840	1850	1850	1770	1670
30	2190	2210	2210	2135	2010
40	2550	2570	2580	2520	2420
50	2900	2945	2965	2935	2830
60	3250	3310	3350	3340	3250

It is evident from the Table that the values of the inductance, of the saturation curve, and of the armature resistance, by chance combine to render the excitation regulation largely independent of the power factor. In normally-proportioned machines the values generally diverge rapidly from each other as the ampere load increases.

The curve for zero power factor is plotted in the upper solid line of Fig. 479. It is interesting to note that for this particular machine it would cross the curve for unity power factor at some slightly higher current output; hence, for higher current outputs, *less excitation would be required for zero power factor than for unity power factor.* The writers are not aware that it has ever before been pointed out that this could occur.

The upper dotted line of Fig. 479 gives a curve of excitation experimentally obtained on this machine for loads with power factors of less than 0.1. This curve intersects the curve for unity power factor, as the theory points out would be the case, but at a somewhat lower point than the intersection of the calculated curves. Nevertheless, it is interesting to find thus confirmed the statement just made, based upon the calculated curves, that for high amperes output, *less excitation would be required for power factor* = 0 *than for power factor* = 1.

Both the experimental curves of Fig. 479 check the calculated values very well up to 30 amperes output, or 50 per cent. over load, while beyond this point the rapidly increasing variation may be accounted for by reason of the rise of resistance due to excessive currents in the conductors; at 50 amperes output the density in these would be 9300 amperes per square inch in cross section. In the calculated curves no allowance has been made for this rise, as it would be impossible to accurately estimate the actual temperature of the embedded conductors; the readings were taken as rapidly as possible to prevent destroying the insulation, and even then the core surface adjacent to that part occupied by the coils attained a temperature of about 100 deg. Cent., or a rise of 80 deg. Cent. This would tend largely to increase the excitation at the higher points, and would also cause the curve of unity power factor to cut that of zero power factor at a lower value, also corresponding more nearly to the observations.

VOLT-AMPERE CURVES

The value of 1670 ampere turns per field spool has already been estimated to be the excitation required to maintain 60 terminal volts with a non-inductive load of 20 amperes.

In Fig. 481 are plotted not only a volt-ampere curve, with this excitation, calculated for non-inductive loads, but also one for loads of zero power factor. These are the two full-line curves of Fig. 481.

The values were derived as follow :—

Unity power factor: Consider the conditions at short circuit. Resistance of the armature = 0.31 ohm. To determine the point at

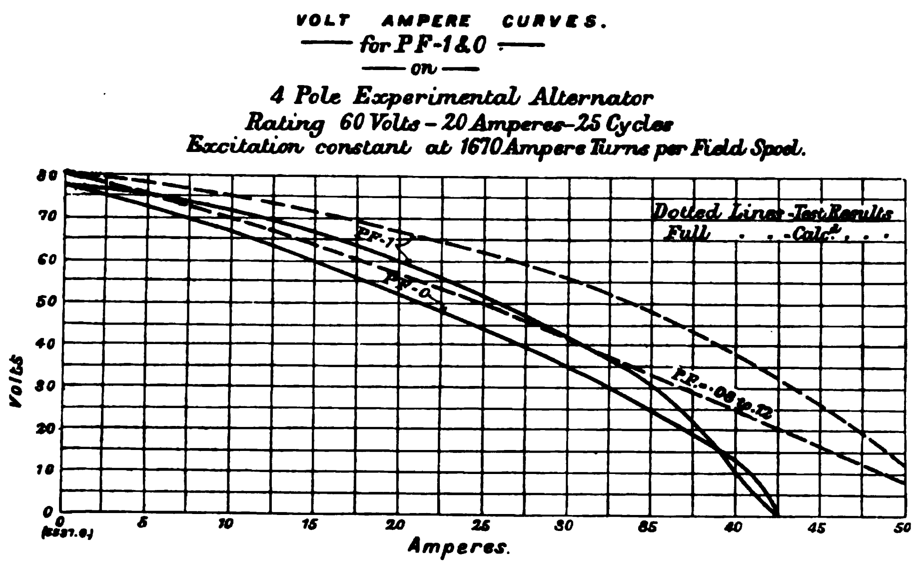


FIG. 481. VOLT-AMPERE CURVES

which the volt-ampere curve meets the axis of abscissæ, one reasons as follows :—The armature turns are then practically fully demagnetising. At 20 amperes the full armature strength = 680 ampere turns per pole-piece. As the current lags nearly 90 deg. behind mid-pole-face position, the armature ampere turns will only be less than the impressed field magnetomotive force by the amount necessary to set up a flux corresponding to 0.31 C volt, if C = the amperes at short circuit. (This neglects magnetic leakage.)

From the no-load saturation curve is taken the value of 170 ampere turns as required for 10 volts.

$$\text{Then, } \frac{C}{20} \times 680 + \frac{0.31\,C}{10} \times 170 = 1670.$$

Solving, we obtain C = 42.5 amperes, and this is the value of the abscissa where the axis is crossed by the curve.

On open circuit the saturation curve shows that the 1670 ampere turns will set up 78 volts, and this is the value of the ordinate where the axis is crossed by the curve.

Calculation for 10 amperes :—

Make the trial assumption of 73 volts.

Internal drop (with 10 amperes) = 3.1 volts.

If the lag is such as to correspond to a value of 2.3 ohms for the reactance, then we have an armature reactance voltage of 23 volts. The diagram is given in Fig. 482.

$$\text{Tan } \phi = \frac{23}{73 + 3.1} = \frac{23}{76.1} = 0.302 \; \phi = 17 \text{ deg.}$$

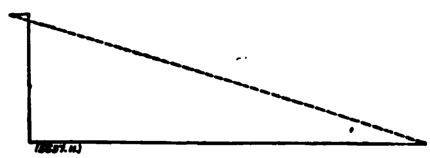


FIG. 482. VECTOR DIAGRAM FOR EXPERIMENTAL ALTERNATOR

and we find from Fig. 476 that at 17 deg. the reactance does equal 2.3 ohms.

$$\text{Sin } \phi = 0.29. \quad 0.29 \times 10 \times 24 \sqrt{2} = 99 \text{ ampere turns demagnetisation.}$$

$$\begin{array}{lr} \text{Saturation magnetomotive force for 76.1 volts} = & 1600 \\ & 99 \\ \hline & 1700 \end{array}$$

Hence our assumption of 73 volts was a little too high; 72 volts would have been about right. The other points for the curve were obtained in the same manner.

For Power Factor = 0

At open circuit and short circuit, the curve cuts the axles at the same point as the curve for power factor = 1, and it is so shown in Fig. 481. The intermediate points remain to be determined.

At 10 Amperes

Fig. 483 represents the conditions: Assume that the value of the ordinate corresponding to 10 amperes will be 67 volts. The armature strength is practically fully demagnetising, and equal to

$$10 \times 24 \times \sqrt{2} = 345 \text{ ampere turns.}$$

Magnetomotive force corresponding to 67 volts will be 1330 ampere turns. Hence, total magnetomotive force = 340 + 1330 = 1670 ampere turns, so that the trial value of 67 volts was the correct value.

It is interesting to note the change which this diagram undergoes with larger currents as the resistance component becomes appreciable; this appears in Fig. 484, which corresponds to the conditions at 30 amperes.

Thirty Amperes

Assume 35 volts (see Fig. 484). The armature ampere turns are, as before, practically entirely demagnetising, and are equal to

$$30 \times 24 \times \sqrt{2} = 1020,$$

but the saturation ampere turns have to correspond to

$$\sqrt{9.3^2 + 35^2} = 36.2 \text{ volts},$$

which (from saturation curve) requires 659 ampere turns. Hence excitation equals 1020 + 650 = 1670 ampere turns. Therefore, the assumption

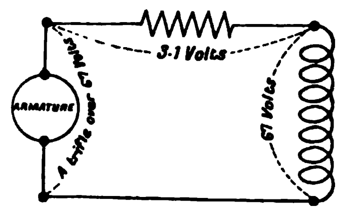


Fig. 483.

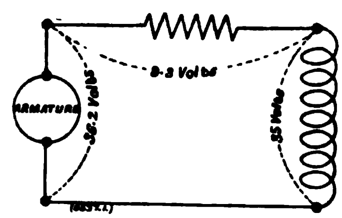


Fig. 484.

Explanatory Diagrams for Experimental Alternator

of 35 volts as corresponding to 30 amperes is correct for the zero power factor volt-ampere curve. The other points were obtained in the same manner.

Table LXXII.—Summary of Results

Amperes Output.	Terminal Voltage. P.F. = 1	Terminal Voltage. P.F. = 0
0	78	78
10	72	67
20	60	52
30	42	35
40	10	13
42.5	0	0

The curves of observed values are also given in Fig. 481, in dotted line. The power factor for the lower curve was, however, from 0.08 to 0.12, never, of course, being absolutely 0.

Short-Circuit Curve

The full-line curves of Fig. 481 cut the axis of abscissæ at 42.5 amperes. They were taken with an excitation of 1670 ampere turns per field spool. The short circuit curve should, therefore, be a straight line passing through zero and through this point. It is drawn full in Fig. 485, and in the same figure the observed curve is shown in dotted line.

Calculation of Saturation Curves for Full-Load Current of 20 Amperes, for Unity and for Zero Power Factor

The value for terminal voltage of 0 is found from Fig. 485 to be 790 ampere turns per field spool at 20 amperes.

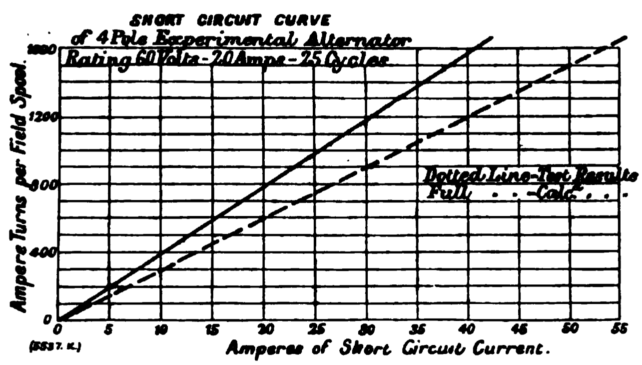


Fig. 485. Short-Circuit Curves

For 20 Terminal Volts

The reactance with 20 amperes may, for a trial value, be taken at 1.6 ohms; hence the reactance voltage = 32. C R drop in armature = 20 × 0.31 = 6.2 volts.

$$\phi = \tan^{-1} \frac{32}{6.2} = \tan^{-1} 1.22 = 51 \text{ deg.}$$

Fig. 476, page 440, shows that the value of the reactance is 1.6 ohms at 51 deg., confirming the assumed value. The diagram for these values is given in Fig. 486.

From Fig. 475, page 439, the magnetising component corresponding to 26.2 volts is found to be 460 ampere turns per field spool. To overcome armature demagnetisation, there will be required

$$24 \times 20 \times \sqrt{2} \times \sin 51 \text{ deg.} = 680 \times 0.78 = 530 \text{ ampere turns.}$$

Total field excitation for 20 terminal volts at 20 amperes at unity power factor = 460 + 530 = 990 ampere turns.

In the same way, values have been calculated for other points, and these are plotted in the left-hand full-line curve of Fig. 487, page 450, in which the left-hand dotted curve gives the observed values.

TABLE LXXIII.—CALCULATED VALUES FOR UNITY POWER-FACTOR. FULL-LOAD SATURATION CURVE

Terminal Volts.	Ampere Turns per Field Spool.
0	790
20	990
40	1280
60	1670
80	2300
90	2900

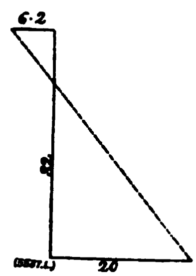


FIG. 486. VECTOR DIAGRAM FOR CALCULATING FULL-LOAD SATURATION CURVE OF EXPERIMENTAL ALTERNATOR

For zero power factor, the calculation is modified. The armature demagnetisation has a constant value of 680 ampere turns for all values of the terminal voltage, and the armature C R drop is in quadrature with the terminal voltage. The calculated values for zero power factor are :—

Terminal Volts.	Ampere Turns per Field Spool.
0	790
20	1040
40	1400
60	1840
80	2430
90	2860

REGULATION CALCULATION FOR 850-KILOWATT ALTERNATOR

Although we have not as yet covered the necessary ground to permit of profitably discussing complete designs, it is, nevertheless, desirable at this stage to describe a large modern alternator, and give the curves of its performance as experimentally obtained, and to compare them with curves determined by the theory as already set forth. It is

believed that it will be generally admitted that the close agreement thus demonstrated to exist between the theoretical and experimental curves will prove its practical usefulness. In the following brief specification, and in Fig. 490, page 453, are given just enough data to carry out the calculation of the curves for the alternator in question.

Specification for a Three-Phase Alternator of the Internal Revolving Field Type:—[1]

Rated output	850 kilowatts.
Connection of windings	Y
Terminal voltage	5000 volts.

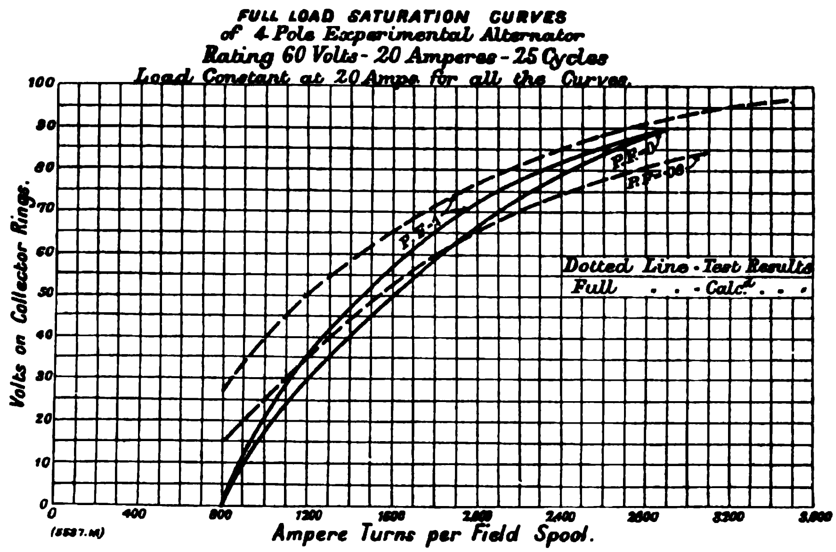


Fig. 487. Full-Load Saturation Curve

Voltage per phase	2800 volts.
Current per phase	$\frac{850,000}{3} \times \frac{1}{2880} = 98.5$ amperes.
Speed	94 revolutions per minute.
Periodicity	25 cycles per second.
Slots per pole-piece on the armature...	6
Slots per pole-piece per phase ...	2

The machine is of the internal revolving field type, with 32 radial salient poles.

Conductors per slot	14
Turns per pole-piece per phase	14
R. M. S. ampere turns per pole-piece per phase ...	1380
Maximum armature magnetomotive force per pole-piece per phase	$\sqrt{2} \times 1380 = 1950$

[1] A more complete specification and description of this Central London Railway alternator is given at the end of this Chapter.

Now, it must here be stated, subject to subsequent explanation,[1] that the total maximum armature magnetomotive force per pole-piece of a machine of this particular type and proportions is about twice the maximum magnetomotive force per pole-piece = 3900.

The experimentally determined no-load saturation curve of the machine is given in Fig. 488. Unfortunately, of the several machines available, it became necessary to take some of the tests upon one and some upon another. This has led to slight discrepancies, mainly with

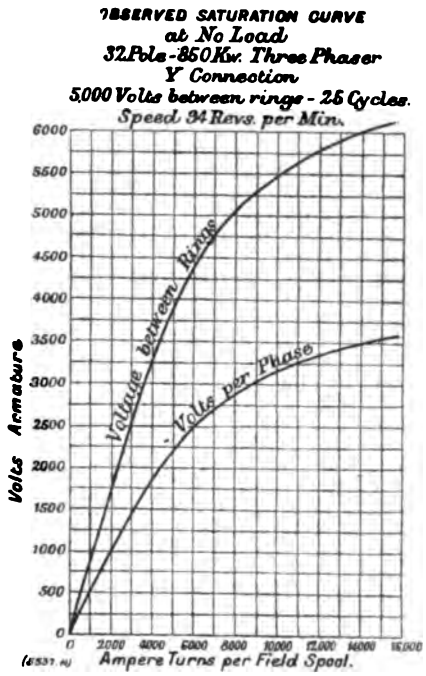


FIG. 488. NO-LOAD SATURATION CURVE

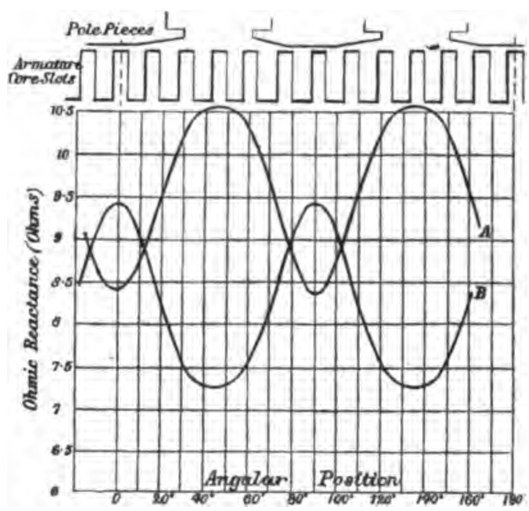


FIG. 489.
REACTANCE CURVES OF 850-KILOWATT ALTERNATOR

relation to the no-load ampere turns corresponding to various voltages. Nevertheless, it is believed that one cannot but admit that the tests, as a whole, correspond very closely with the calculated results.

In Fig. 489 are given two reactance curves, A and B, the first taken for the reactance of one phase when there are three phasially related currents in all three phases—the normal condition—and the second taken with current in one phase only. Both curves are given in order to point out that in a machine of these proportions, at any rate, the current in the other two windings does not very much affect the average value of the inductance of one winding; hence, in cases where it is only

[1] See description of the Central London Railway alternator at the end of this Chapter.

practicable to make determinations on but one phase, useful conclusions can nevertheless be drawn. In this case, however, curve A should be used as the basis for calculations. The inductance does not vary greatly at different positions, and it is amply exact to use, throughout the calculations, the average values of the reactance for all positions, which is 9.6 ohms at 25 cycles.

$$\text{Reactance} = 2\pi n l.$$

$$\therefore l = \frac{9.6}{2 \times 3.14 \times 25} = 0.061 \text{ henry.}$$

There are 32 poles, and 16 groups of coils per phase.

$$\therefore \text{Inductance per group of coils} = \frac{0.061}{16} = 0.0038 \text{ henry.}$$

Expressed in C.G.S. lines, this is 380,000 lines, linked with a coil.

The gross length of armature laminations is 14.5 in.

$$\therefore \text{Linkage of lines per inch} = \frac{380{,}000}{14.5} = 26{,}300.$$

One side of one group of coils is wound in two adjacent slots, there being 14 conductors per slot, or 28 total turns in series per group of coils, as seen in Fig. 490.

Hence there are $\frac{26{,}300}{28^2} = 33.5$ lines per ampere turn per inch of length of armature laminations, for the average of all positions.

From the saturation curve of Fig. 488 and the reactance curve of Fig. 489, and from the known windings of the armature, which give a resultant armature magnetomotive force of 3900 maximum ampere turns in the position of maximum demagnetisation, the other characteristic curves of the machine will next be calculated and plotted. The only especial point to be kept in mind in these calculations, which will differ from those for a single-phase machine, is that it is clearer in some cases to consider each phase separately. For this purpose Fig. 488 gives also a saturation curve in terms of the voltage per phase, which bears to the voltage between collector rings the relation of 1 to 1.73, or of 2880 to 5000.

Calculation of Curve of Excitation Regulation for Unity Power Factor

This is a curve showing the ampere turns per field spool which are required for maintaining a constant collector-ring voltage of 5000 volts between any pair of collector rings, or 2880 volts per phase (*i.e.*, from any collector ring to the common connection of the "Gamma") for all values of the current output, from 0 amperes up to and above the full-load rating of 98.5 amperes, with non-inductive external load.

(1) Amperes = 0. From the lower saturation curve of Fig. 488, page 451, the required excitation for the normal potential of 2880 volts per phase is 7650 ampere turns per field spool.

(2) Amperes = 98.5 (full-rated load). The reactance voltage = 9.6 × 98.5 = 945 volts.

$$\text{Tan}^{-1}\frac{945}{2880} = \tan^{-1} 0.328 = 18 \text{ deg.} \quad \text{Sin } 18 \text{ deg.} = 0.31.$$

Maximum resultant armature strength = 3900 ampere turns.

Demagnetising component = 0.31 × 3900 = 1210 ampere turns.

Hence, at 98.5 amperes load (power factor = 1) there is required

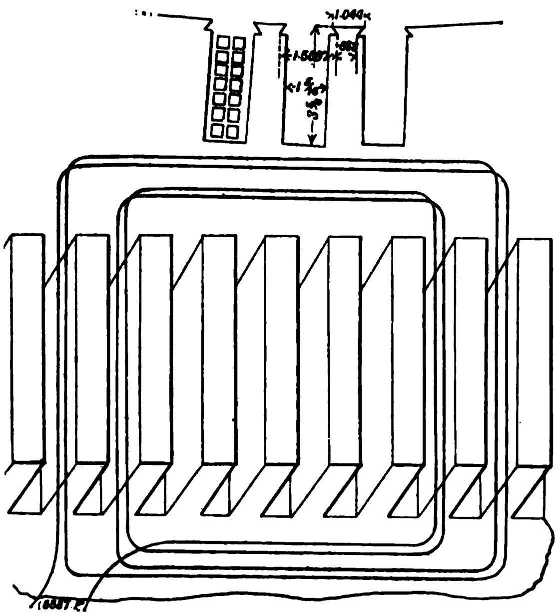


Fig. 490. Slots of 850 Kilowatt Three-Phase Generator

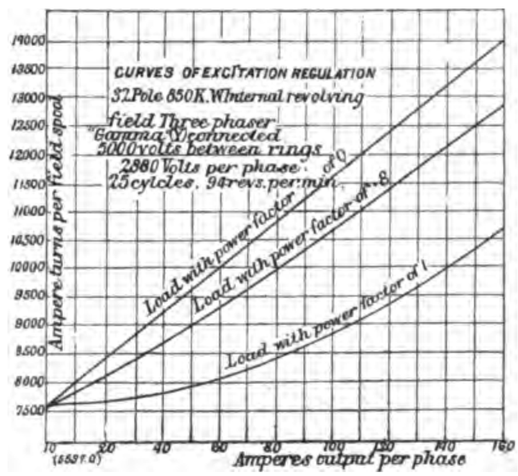


Fig. 491. Curves of Excitation Regulation

(for 2880 volts per phase) a total excitation of 7650 + 1210 = 8860 ampere turns per field spool. (The corresponding observed value was 9000 ampere turns.) Similar calculations for other loads yield the results plotted in the curve of Fig. 491 for unity power factor.

Calculation of Curve of Excitation Regulation for Zero Power Factor

For this case the armature ampere turns are fully demagnetising, hence at full load there will be required an excitation of 7650 + 3900 = 11,550 ampere turns per field spool. The other calculated values will be on a straight line passing through the value of 7650 ampere turns for 0 amperes output, and 11,550 ampere turns for 98.5 amperes output. This curve for zero power factor is also drawn in Fig. 491.

CALCULATION OF CURVE OF EXCITATION REGULATION FOR POWER FACTOR OF .8

First, 98.5 amperes output. The conditions are shown in the diagram of Fig. 492.

Cos 37 deg. = 0.8. D A C = 37 deg.

A C = A D = 2880 = volts per phase.

A B = 945 = reactance voltage per phase for 98.5 amperes.

$$A F B = \tan^{-1} \frac{A B + E D}{A E}$$

E D = A D sin 37 deg. = 2880 + 0.6 = 1720.

A E = A D cos 37 deg. = 2880 × 0.8 = 2300.

$$\therefore A F B = \tan^{-1} \frac{945 + 1720}{2300} = \tan^{-1} 1.15 = 49.2 \text{ deg.}$$

Sin 49.2 deg. = 0.755.

Demagnetising component of total armature strength = 0.755 × 3900 = 2950 ampere turns.

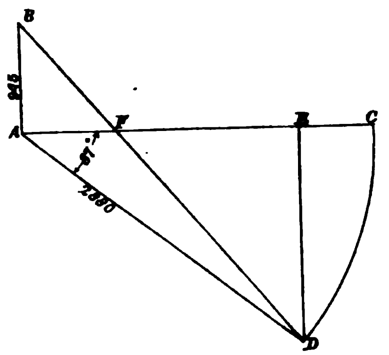


FIG. 492. FULL LOAD

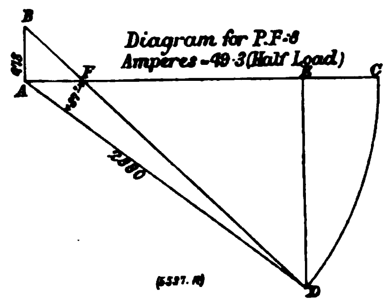


FIG. 493. HALF LOAD

VECTOR DIAGRAMS FOR EXCITATION REGULATION CALCULATIONS. POWER FACTOR = 0.8

$$\begin{aligned} \text{Sin } \phi &= \sin A F B. \\ &= \sin \left(\tan^{-1} \frac{473 + 2880 \sin 37 \text{ deg.}}{2880 \cos 37 \text{ deg.}}\right) \\ &= \sin (\tan^{-1} 0.95) \\ &= \sin 43.5 \text{ deg.} = 0.69. \end{aligned}$$

$$\text{Demagnetising component} = 0.69 + \frac{3900}{2} = 1340.$$

7650 + 1340 = 8990 ampere turns required to maintain 2880 volts per phase with a load of 49.3 amperes at power factor = 0.8.

Therefore, with full-load current of 98.5 amperes, at power factor = 0.8, there will be required to maintain a potential of 2880 volts per phase, an excitation of 7650 + 2950 = 10,600 ampere turns per field spool.

For other values of the current, and also for other power factors, the calculations are similar. A diagram for half-load current and power

factor = 0.8 is given in Fig. 493, with the corresponding calculations below it. Table LXXIV. exhibits the calculated results, which will also be found plotted in the curves of Fig. 491, page 453.

TABLE LXXIV.—EXCITATION REGULATION

Amperes Output.	Ampere Turns per Field Spool Required to Maintain 2880 Volts per Phase (5000 Volts between Rings) for Various Loads.		
	P. F. = 0.	P. F. = 0.8.	P. F. = 1.
0	7,650	7,650	7,650
25	8,640	8,290	7,730
50	9,630	9,015	7,970
75	10,620	9,810	8,380
98.5	11,550	10,600	8,860
125	12,600	11,550	9,540
150	13,590	12,470	10,310

EXPERIMENTAL TESTS OF EXCITATION REGULATION

The excitation regulation curve for unity power factor as experimentally obtained is given in curve A, of Fig. 494, page 456, and for the lowest obtainable power factors, in curve B of the same figure. The corresponding calculated curves of Fig. 491, page 453, are reproduced in dotted lines.

POWER FACTOR CURVE

In Fig. 495 is plotted a curve showing the excitation corresponding to the full-load current of 98.5 amperes, and to the normal potential of 2880 volts per phase (5000 volts between collector rings) for all values of the power factor. These results have been taken, partly from the preceding curves (Fig. 491), and partly from other values similarly calculated, but for other power factors.

CALCULATION OF SATURATION CURVE WITH FULL-LOAD CURRENT OF 98.5 AMPERES

1. *Unity Power Factor.*—For 0 volts per phase. Excitation will be about 3900 ampere turns per field spool, or rather a slight trifle in excess of this required to send 98.5 amperes through the ohmic resistance of the armature winding.

For 1000 volts per phase:—

The conditions are shown diagrammatically in Fig. 496, page 457, in

which A B represents the reactance voltage, and A C the terminal voltage per phase.

$$A\,C\,B = \tan^{-1}\frac{945}{1000} = \sin^{-1} 0.69$$

$$0.69 \times 3900 = 2690.$$

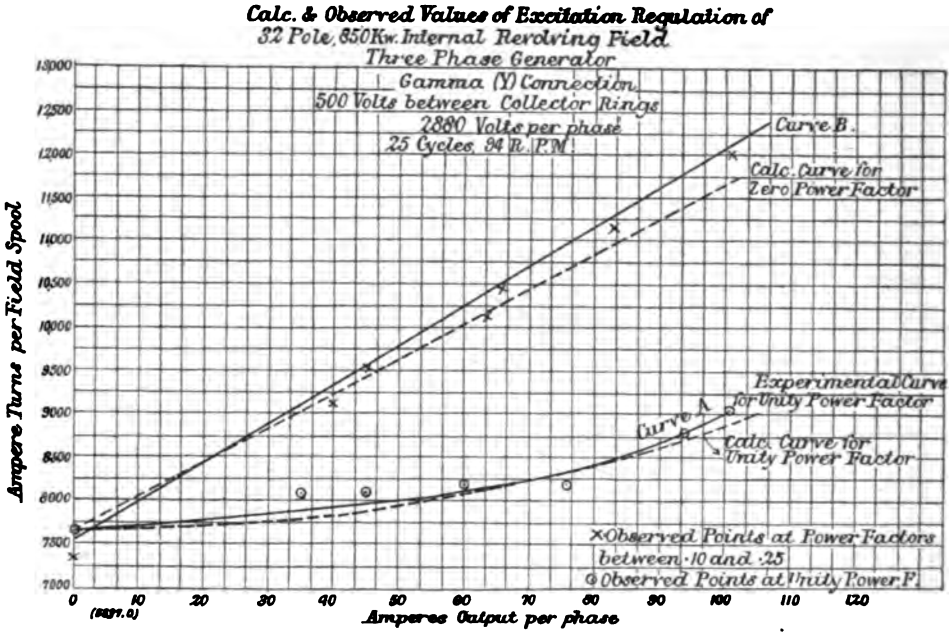


FIG. 494. EXCITATION REGULATION CURVES

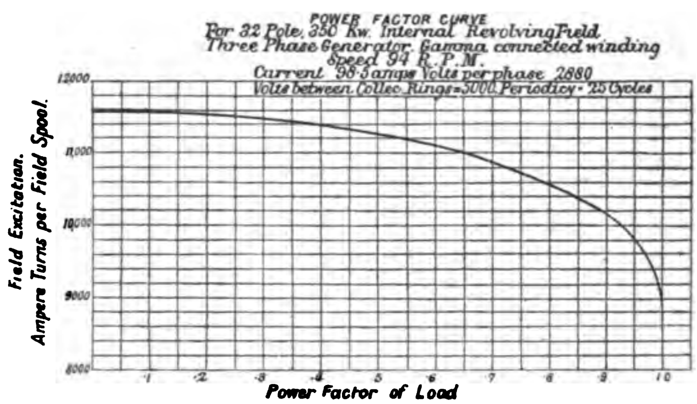


FIG. 495. EXCITATION CURVE, FULL-LOAD CURRENT

Therefore the demagnetising component of the total required excitation = 2690 ampere turns. From the lower saturation curve of Fig. 488, page 451, the saturation component corresponding to 1000 volts is seen to be 2000 ampere turns. Hence there is required a total excitation of

2690 + 2000 = 4690 ampere turns per field spool. In the same way, the conditions for 2000 volts per phase are shown in Fig. 497. The value for full-load voltage (2880 per phase) has already been calculated to be 8860 ampere turns. Fig. 498 gives a diagram and calculation for 3500 volts per phase.

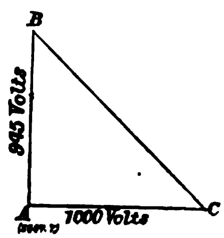


FIG. 496.

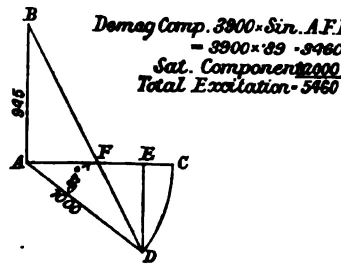
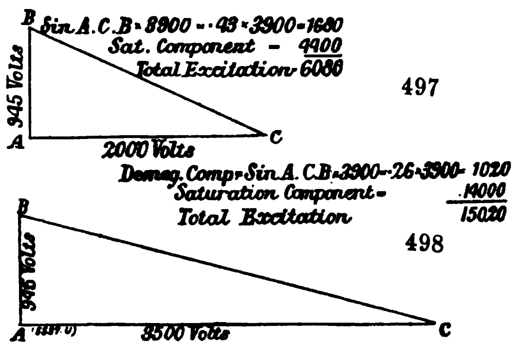


FIG. 499.



FIGS. 497 AND 498.

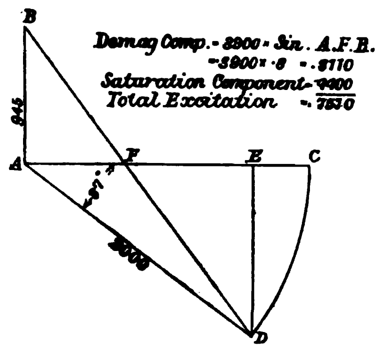


FIG. 500.

2. *Zero Power Factor*.—In this case, all that is required is to add to the saturation components the full armature strength of 3900 ampere turns. Thus :—

TABLE LXXV.—VALUES FOR 0 POWER FACTOR.

Voltage per Phase.	Saturation Component.	Demagnetisation Component.	Total Excitation.
0	0	3,900	3,900
1000	2,000	3,900	5,900
2000	4,400	3,900	8,300
2880	7,650	3,900	11,550
3500	14,000	3,900	17,900

3. *Power Factor* = 0.8.—The case for 1000 volts per phase is given in Fig. 499, for 2000 volts in Fig. 500, and for 3500 volts in Fig. 501.

All these saturation curve values (as well as those for no load) are brought together in the annexed Table, and plotted in Fig. 502, page 460.

TABLE LXXVI.—SATURATION CURVE VALUES.

Volts per Phase.	Volts at Collector Rings.	Ampere Turns per Field Spool.			
		Amperes = 0.	Amperes = 98.5 P.F. = 1.	Amperes = 98.5 P.F. = 0.8.	Amperes = 98.5 P.F. = 0.
0	0	0	3,900	3,900	3,900
1,000	1,730	2,000	4,690	5,460	5,900
2,000	3,460	4,400	6,080	7,510	8,300
2,880	5,000	7,650	8,860	10,600	11,550
3,500	6,060	14,000	15,020	16,870	17,900

In Fig. 502 the dotted line curve is plotted from the results of test with full-load current and unity power factor.

THE "SHORT-CIRCUIT" CURVE

In Fig. 503, page 461, the full line represents the relation between the armature ampere on short circuit, and the corresponding required field excitation. Under these conditions, the armature ampere turns are in direct opposition to the field ampere turns; hence, at 98.5 amperes per phase, when the total armature strength is 3900 ampere turns per pole-piece, there should be required a field excitation only just enough in excess of 3900 ampere turns per pole-piece to set up sufficient potential to overcome the C R drop in the armature windings (about 30 volts in the case in question), and to supply the losses due to magnetic leakage. There is shown in dotted line the observed "short-circuit" curve.

THE VOLT-AMPERE CURVE

In calculating the excitation regulation curve for unity power factor, the excitation required for 5000 terminal volts (2880 volts per phase) and 98.5 amperes was determined to be 8860 ampere turns per field spool.

With this excitation constant, and varying resistance of the external load, the upper full-line curve of Fig. 504 represents the calculated values. Points are also plotted representing the results of tests.

Calculation for Unity Power Factor

To illustrate the method of procedure according to which the upper

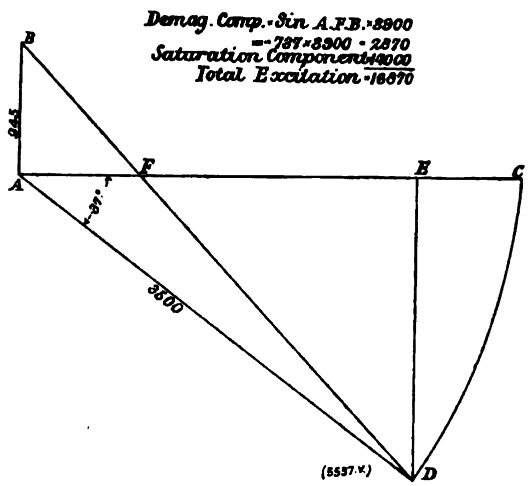


Fig. 501.

curve of Fig. 504 was derived, a calculation is carried out for 150 amperes,

Take $\frac{4350}{\sqrt{3}}$ = 2150 volts as a trial assumption :—

Reactance voltage = 9.6 × 150 = 1440 volts.

$\text{Tan}^{-1} \frac{1440}{2510} = \tan^{-1} 0.573 = 30$ deg.

Sin 30 deg. = 0.5.

$0.5 \times \frac{150}{98.5} \times 3900 = 2960.$

Ampere turns per field spool = 8860.
Demagnetising ampere turns = 2960.
Residual ampere turns ... = 5900.

Corresponding voltage from saturation curve (Fig. 488, page 451) = 2490 volts.

Hence the trial assumption of 2510 volts was practically correct.

We conclude that 150 amperes corresponds to 2500 volts.

The other points of the curve were calculated by the same process.

Calculation for Zero Power Factor

The two extremes of the curve—*i.e.*, open circuit and short circuit—will have the same values as for unity power factor. The other values are shown in the lower curve of Fig. 504. From the saturation curve for zero power factor, given in Fig. 502, the value of the voltage for 8860 ampere turns excitation is 2200 volts at 98.5 ampere. Other

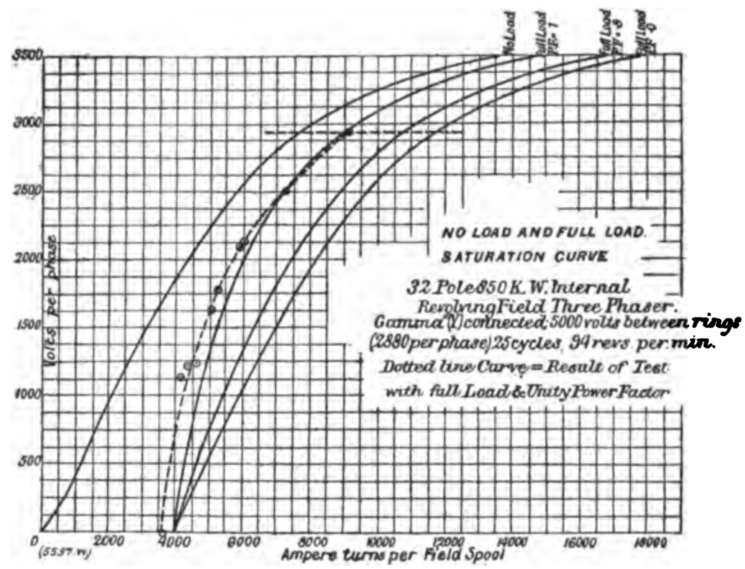


Fig. 502. Saturation Curves

points of the curve have been calculated by the same method as the value at 150 amperes, for which the calculation is given below:—

Ampere turns per field spool	... ...	**8860**
Demagnetising ampere turns $\times \frac{150}{98.5} \times 3900$	... ...	**5920**
	Residual ampere turns	**2940**

Volts (from saturation curve) = 1400.

The results of tests both at unity power factor and at very low-power factors, are also indicated in Fig. 504.

Up to this point, rough representative values have been used for the inductance per unit length of armature laminations, in cases where experimental observations of the inductance were not available. This has been desirable in order not to divert attention from the general lines of the method of predetermining the characteristic curves. But the matter of predetermining the inductance of the windings is one of

considerable importance; and, before proceding further, it is desirable to consider it much more thoroughly, in the light of additional experimental data now available.

In continuous-current commutating machinery it is the inductance of the turns undergoing commutation at the brushes which possesses the chief interest. This can be estimated with a fair degree of exactness—first, because the range of shapes of coils and sizes of slots is not extremely great; and, secondly, because the required value of the inductance is that corresponding to the position of the coil in the open space between pole-tips, *i.e.*, away from the influence of the pole-face. Numerous tests on

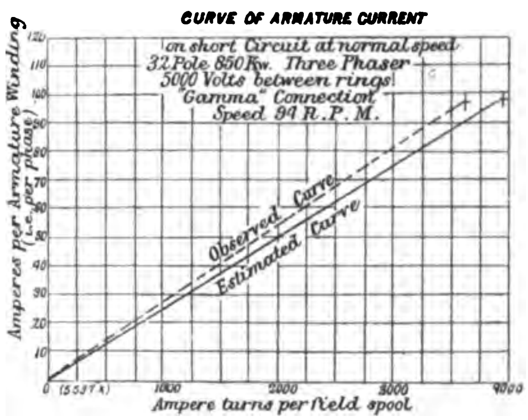


FIG. 503. CURVE OF ARMATURE CURRENT

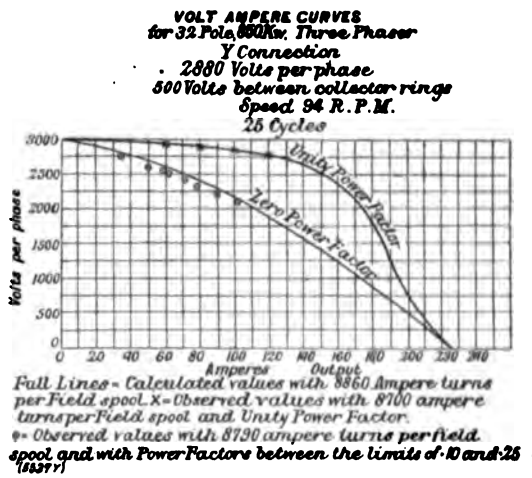


FIG. 504. VOLT-AMPERE CURVES

such coils have shown the inductance of the coils under these conditions to be about the same when the armature is in place in the field frame as when it is free in air. In alternating-current machinery it is required to be able to estimate the inductance for all positions of the armature with respect to the magnetic circuit, and not for a small compact group of turns, but often for more or less distributed windings. Moreover, a greater variety of shapes of coils and sizes and shapes of slots are encountered.

It will, however, be desirable to begin the study of the subject by examining the results for windings, first quite free in air, and secondly in armatures removed from the rest of the magnetic circuit.

Coils Free in Air

Professor Perry gives the following approximate formula for the inductance L (in centimetres)[1] of a cylindrical spool of N turns free in air, the spool having, as dimensions in centimetres, a width w, mean radius r, and height of winding h, the formula applying for those cases where $\frac{w}{r}$ and $\frac{h}{r}$ are very small:

$$L = \frac{N^2 r^2}{0.0184\, r + 0.031\, h + 0.035\, w}.$$

Solving this for a coil of the cross-section of 1 square centimetre

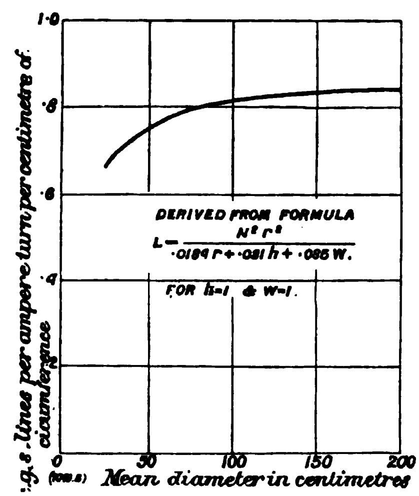


Fig. 505.

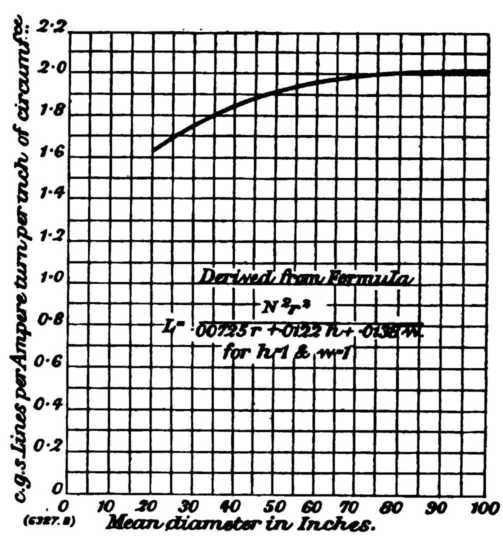


Fig. 506.

Inductance Curves for Coils Free in Air

for various diameters, we derive the curve given in Fig. 505; and for a similar corresponding curve for a coil of a cross-section of 1 square inch, and of various diameters, as given in Fig. 506, with the dimensions of the spool in inches, this becomes:—

$$L \text{ (in centimetres)} = \frac{N^2 r^2}{0.00725\, r + 0.0122\, h + 0.0138\, w}.$$

The curves of Fig. 507 give the corresponding values for square cross-sections of coil for diameters of 50, 100, and 200 centimetres, and in Fig. 508 are given curves for square cross-sections of coil for diameters of 30 in., 50 in., and 100 in. (see page 464).

[1] To reduce L to henrys, multiply by 10^{-9}, and to reduce to linkage of turns and C.G.S. lines, multiply by 10^{-1}.

These curves (Figs. 505 to 508) have been found, by experiment, to hold approximately for cases where the shapes of the coils depart very considerably from the circular form. Figs. 509 and 510 show the results of an especially instructive test in which a hexagonal coil, of the dimensions shown in Fig. 511 was distorted gradually from a width of 27.5 in. (70 centimetres) down to a width of 7.9 in. (20 centimetres), the inductance only decreasing from 0.5 to 0.37 C.G.S. line per inch length (1.22 to 0.95 per centimetre length) for this great range of widths.

The results shown in Figs. 509 and 510 were obtained with current

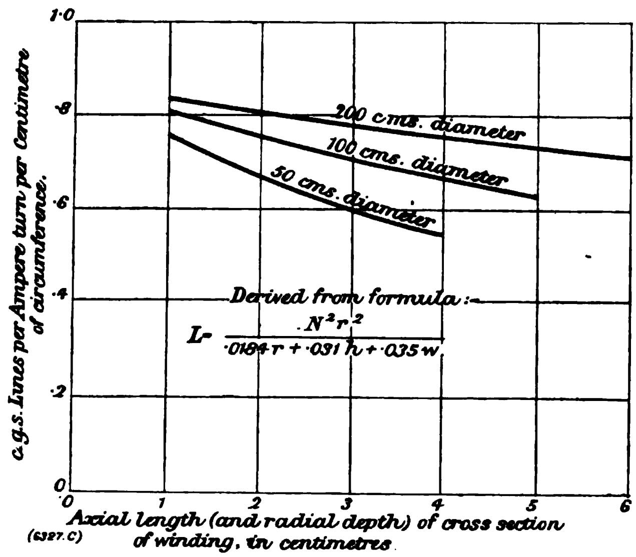


FIG. 507. INDUCTANCE CURVES

from a machine giving 23 per cent. higher values than a sine wave machine.

The curves of Figs. 505 to 508 may be employed for roughly estimating the inductance per centimetre and per inch of those portions of the winding not embedded in the armature slots. These portions may be termed the "free length," as distinguished from the "embedded length."

For continuous-current machines, where the coil undergoing commutation (*i.e.*, temporarily short-circuited under the brushes), generally consists of but a single group of concentrated turns, of which Fig. 512, page 466, is a typical example, it has been found amply exact to estimate the inductance of the "free length" on the basis of 0.8 C.G.S. line per ampere turn per centimetre of "free length," or 2.0 lines per inch of "free length"). In alternating-current machinery it would generally be

less. For considering the case of uni-coil windings, the coil is generally of a large cross-section, often from 1 to 3 centimetres wide, and several centimetres deep; and for coils of larger cross-sections, the curves of Figs. 507 and 508 show a pronounced downward tendency. If, on the other hand, the winding is distributed, as in most modern alternators and in induction motors, the individual coils will be shallow, but the group of coils will—even for polyphase windings—be quite wide. Hence, one rarely meets with cases of alternating current windings where the inductance of the end connections should be estimated at more than

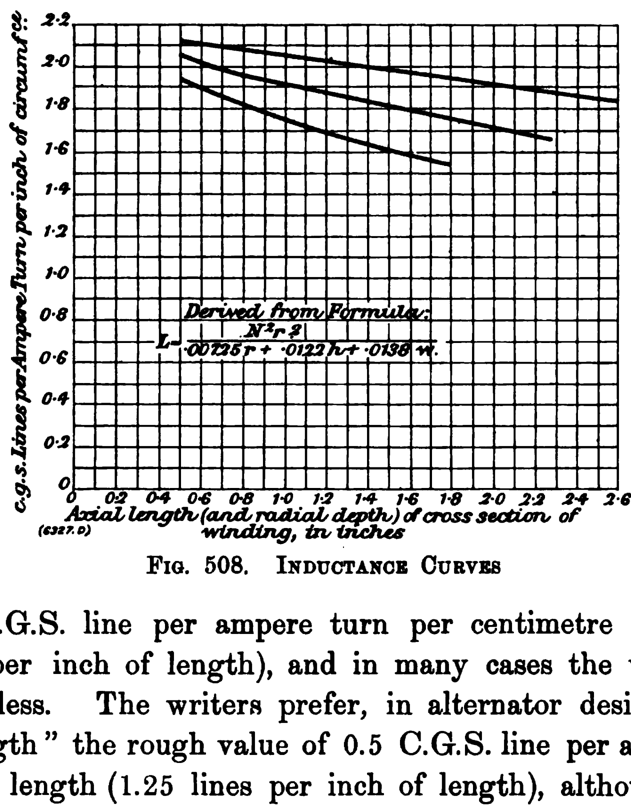


FIG. 508. INDUCTANCE CURVES

0.5 to 0.6 C.G.S. line per ampere turn per centimetre of length (1.25 to 1.5 lines per inch of length), and in many cases the value would be considerably less. The writers prefer, in alternator design, to take for the "free length" the rough value of 0.5 C.G.S. line per ampere turn per centimetre of length (1.25 lines per inch of length), although in extreme cases it is sometimes worth while to examine the proportions with a view to choosing a more suitable value. Examples of the arrangement of the end connections (the "free length") are shown in Figs. 513 to 521, pages 467 to 469.

Setting the polar pitch (*i.e.*, the gap circumference per pole-piece), equal to τ, the "free length" may be roughly taken at $3\,\tau$. For machines for 10,000 volts or more, the "free length" would be somewhat greater, approaching 4.0 in extreme cases. The alternative to such a rough approximation for the "free length" is to make rough preliminary

drawings, and prior to a final decision on the general lines of design; this involves annoying interruptions to the calculations, and, as a matter of fact, the results scaled off from such drawings generally reveal a value for the "free length" not much different from 3 τ.

The Inductance of Coils Laid on the Surface

Tests are available on two coils, A and B, the sections of which are shown in Fig. 522, where the other important dimensions are also given. (See page 469.)

Eliminating the influence of the end connections in both cases, on the basis of 0.8 line per ampere turn per centimetre of "free length,"

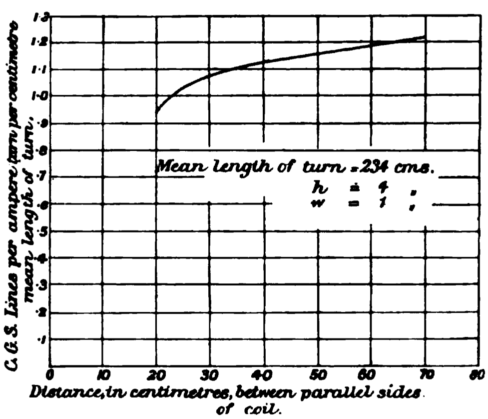


Fig. 509.

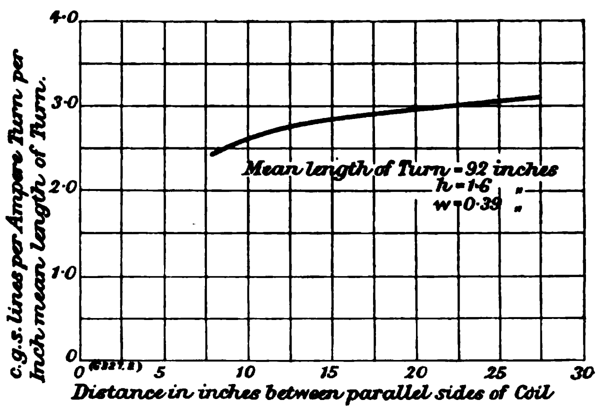


Fig. 510.

Inductance Curves

or 2 lines per inch (the groups being of such small cross-sections), the observations gave the following results:—

For Coil A.—1.9 lines per ampere turn per centimetre of length laid on iron laminations (4.8 lines per inch).

For Coil B.—2.6 lines per ampere turn per centimetre of length laid on iron laminations (6.6 lines per inch).

One would be inclined to take for surface-wound armatures the approximate value of 2 lines per ampere turn per centimetre of length (5 lines per inch) laid on iron laminations for coils of the above proportions, the values decreasing for wider coils.

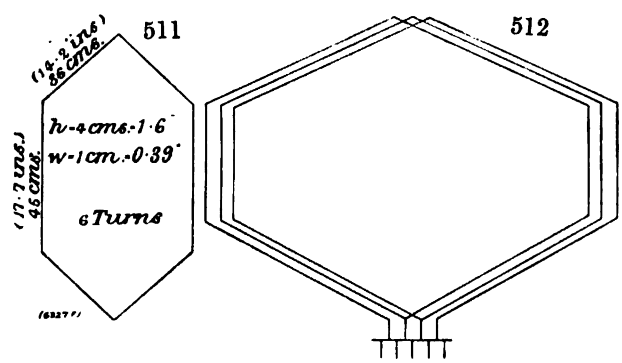
The Inductance of the Embedded Portions of Windings

To obtain a general idea of the extent of the influence of the shape of the slot, five models were built with the winding and slot dimensions shown in Fig. 523, page 469.

Making allowance for the end connections (on the basis of 0.8 line per ampere turn per centimetre of "free length," or 2 lines per inch), the values for the embedded portions are as shown in the following Table :

TABLE LXXVII.—VALUES FOR INDUCTANCE OF EMBEDDED PORTIONS OF WINDINGS

Model.	Lines per Centimetre of Embedded Length.	Lines per Inch of Embedded Length.
1	1.9	4.8
2	2.8	7.1
3	3.2	8.1
4	4.2	10.7
5	7.5	19



FIGS. 511 AND 512.

Models 2, 3, and 4 may be said to represent the extreme limits encountered in practice for parallel-sided open slots.

It is desirable to note the influence of the depth in the slot. Tests were made on a coil for the three positions shown in Fig. 524, page 469, and the results are given in the following Table :—

TABLE LXXVIII.—VALUES ACCORDING TO THE DEPTH IN THE SLOT

Position.	Lines per Centimetre of Embedded Length.	Lines per Inch of Embedded Length.
Coil at bottom of slot	7.2	18.3
Top of coil just level with top of slot ...	4.2	10.7
Bottom of coil just level with top of slot ...	2.6	6.6

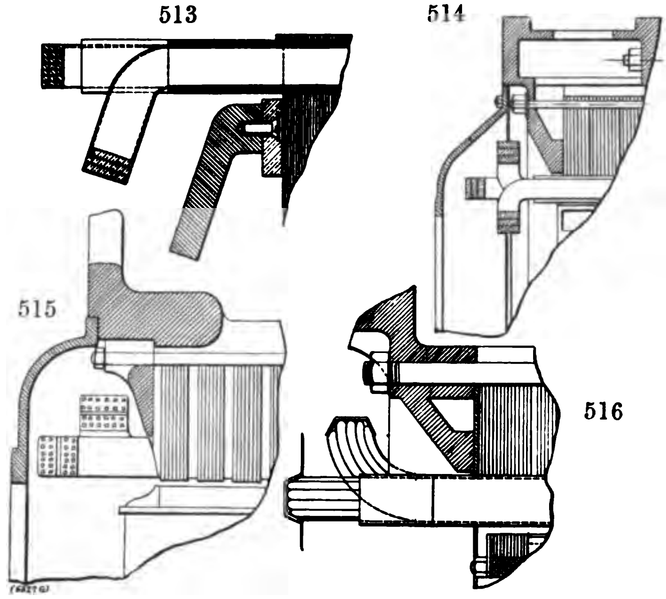
the values representing the flux due to the embedded length alone.

Partly closed over and totally enclosed slots would, per single coil, have still greater values for the inductance, say 7 to 14 C.G.S. lines per ampere turn per centimetre of embedded length (18 to 36 lines per inch).

All these values are applicable to single coils or small groups of coils.

We must next consider the case of distributed windings, for in alternating-current windings, as already pointed out, it is not merely a

513 514



515 516

FIGS. 513 TO 516. TYPES OF ARMATURE END WINDINGS

small group of turns temporarily short-circuited at the brushes with which we have to deal, but—except in the case of uni-coil windings—more or less broad bands of coils covering considerable angular widths of the armature circumference. Such spread-out windings have less inductance as arbitrarily expressed in C.G.S. lines per ampere turn per centimetre of length, because there is very incomplete mutual linkage of all the flux with all the turns; and a rough idea of the extent of this decrease in the inductance may be formed by a consideration of the results of the following tests.

Five sets of punchings were prepared, of the same external size, but with different numbers of slots, namely, with 1, 2, 3, 4, and 6 slots

per pole-piece. The slots were so proportioned that the ratio of width to depth was the same for all five models. The punchings were cut from annealed transformer iron, about 0.38 millimetre thick, and built up to a depth of 63 millimetres. Each sheet was japanned on one side only, and the japanning may be taken as corresponding to some 10 per

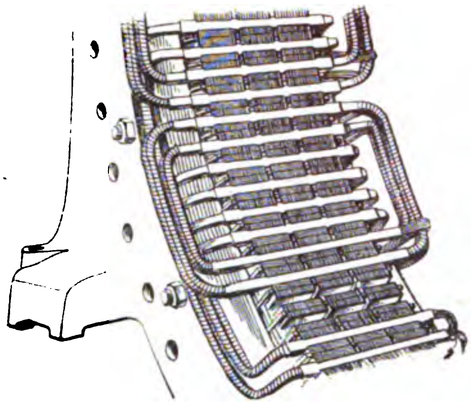


Fig. 517.

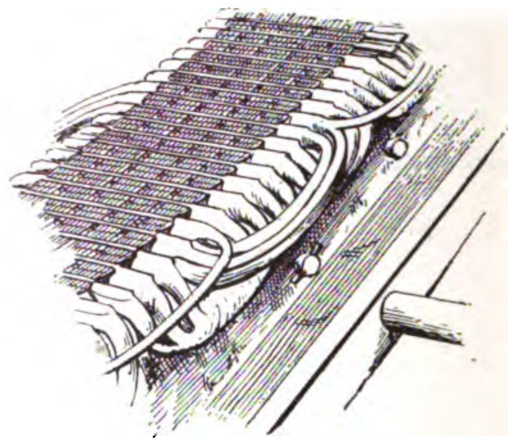


Fig. 518.

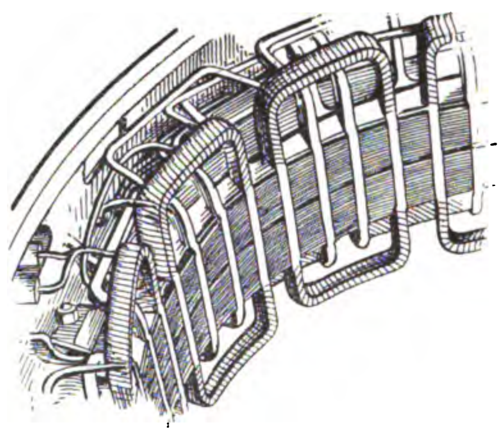


Fig. 519.

Types of Alternator Armature Windings

cent. of the total depth. The laminations were held together by end plates of manganese steel 6.4 millimetres thick, bolted together by means of insulated brass bolts. The coils were wound on formers, taped up, and forced into the slots. The wire used was No. 14 S.W.G. (2.04 millimetres bare diameter) and 144 turns were wound on each set, the total turns being evenly distributed among the slots. Engravings of

the five sets are given in Figs. 525 to 529, pages 470 and 471. The data contained in Table LXXIX. relate to these five models.

While fundamental quantitative results were not the purpose of these tests, the models being too small, it may be pointed out that the approximate equivalent diameter of coil is 13 centimetres, and the

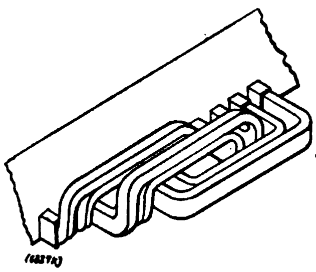


Fig. 520.

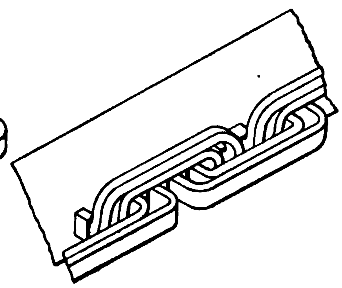


Fig. 521.

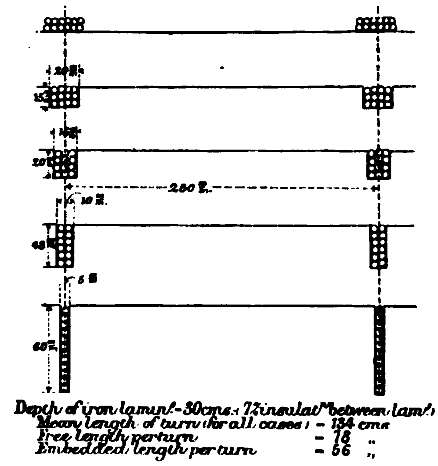


Fig. 523.

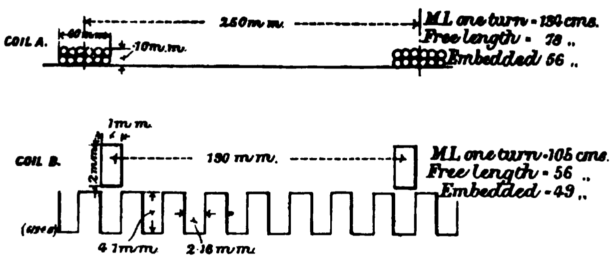


Fig. 522.

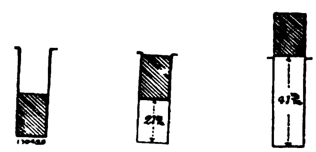


Fig. 524.

Coils used in Inductance Tests

Table LXXIX.—Particulars of Test Windings

Size of Slot in Millimetres.	Number of Slots.	Number of Coils.	Turns per Coil.	Total Turns.	Measured Resistance (Ohms at 20 Deg. Cent.).	Corresponding Mean Length of Turn. Centimetres.
36.8 × 24.2	1	1	144	144	0.33	43
26.2 × 17.2	2	2	72	144	0.31	41
21.4 × 14.0	3	3	48	144	0.29	38
18.4 × 12.1	4	4	36	144	0.31	41
15.0 × 9.9	6	6	24	144	0.31	41

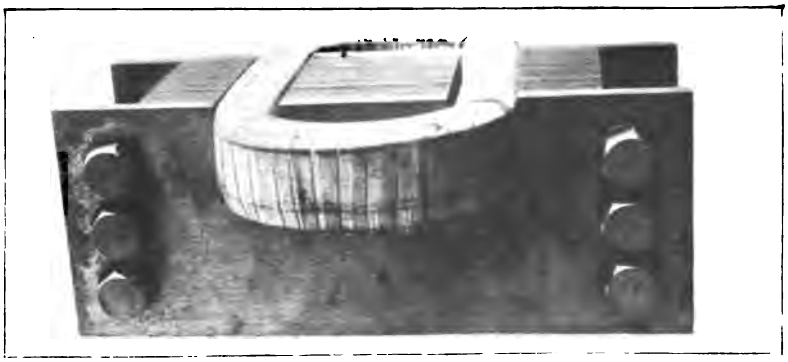


FIG. 525.

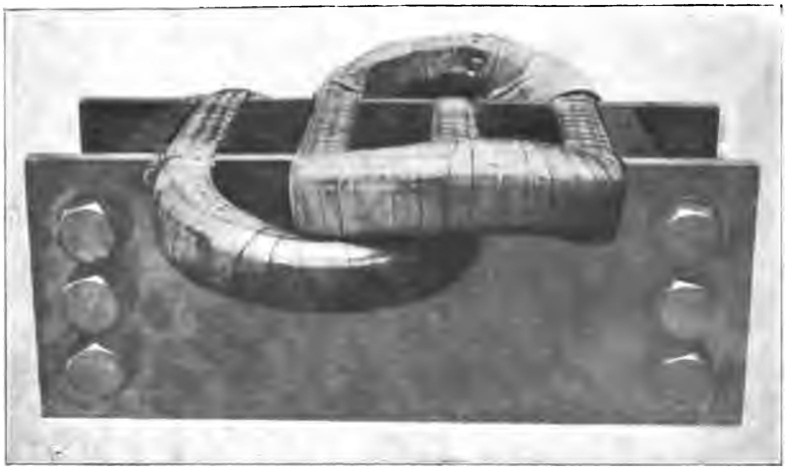


FIG. 526.

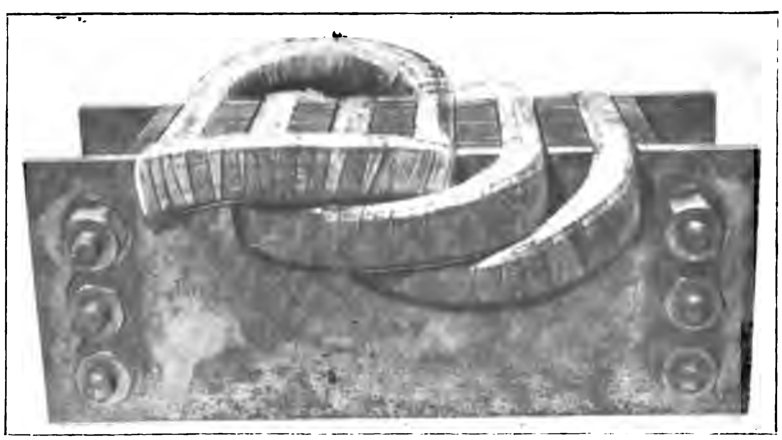


FIG. 527.

MODELS OF WINDINGS USED FOR INDUCTANCE TESTS

approximate equivalent cross-section of coil for the first model is about 3 centimetres square. For such dimensions Professor Perry's formula would not apply. One would, however, infer from the shape of the curves of Figs. 505 to 508, that there would be probably not over 0.3 C.G.S. line per ampere turn per centimetre of "free length" for the uni-slot model, and still less for the other models; hence the magnetomotive

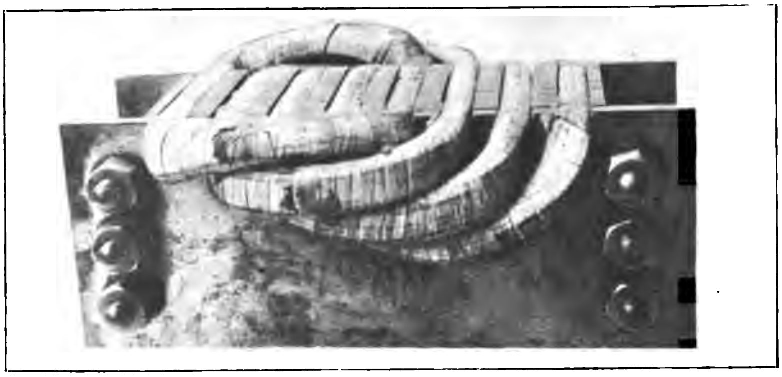


FIG. 528.

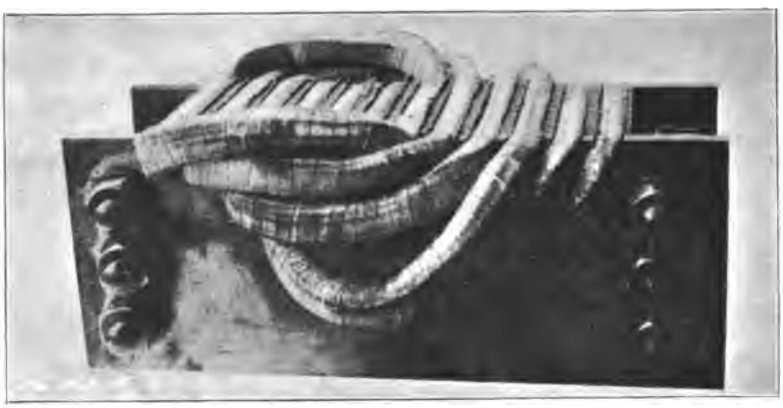


FIG. 529.

MODELS OF WINDINGS USED FOR INDUCTANCE TESTS

force of the "free length" would not affect the results by more than some 10 to 20 per cent.

In the curves of Figs. 530 and 531 are given the results obtained on these models when free in air—*i.e.*, removed from any magnetic material. It is interesting to observe that, for the 6-coil model, the inductance is still 45 per cent. of that of the uni-coil model; and when it is pointed out that these two models represent very extreme cases

one feels greater confidence in employing representative values without undue concern as to the precise slot dimensions in individual cases. As already pointed out, these models are too small to serve suitably for a basis for obtaining useful fundamental constants, being intended for ascertaining the approximate percentage decrease in the inductance secured by distributing a winding of a given number of turns in many slots.

The Influence of Magnet Frame and Pole-Pieces

We now come to the most difficult part of the subject, and a part where the difficulties are increased by a dearth of experimental data. The data and curves heretofore given have all related to windings

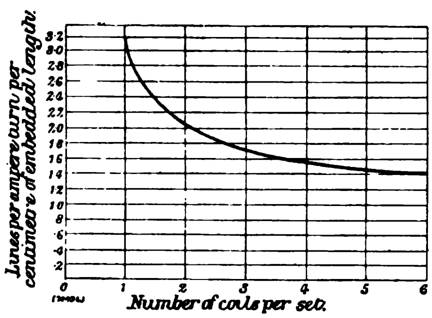


Fig. 530.

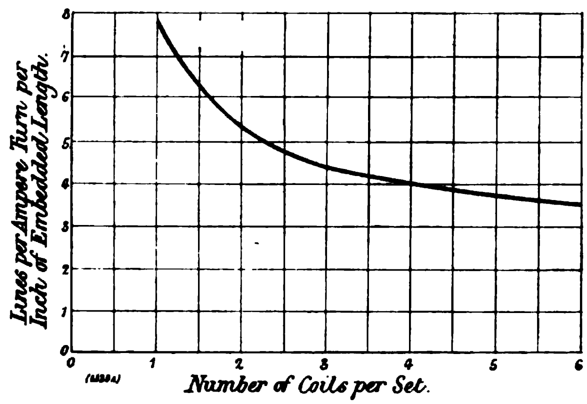


Fig. 531.

Inductance of Test-Model Coils in Air

removed from the neighbourhood of the field structure. As is well known, the proximity of additional magnetic material, so situated as to decrease the reluctance of the magnetic circuit, will have a tendency to increase the values of the inductance. But with windings embedded in completely closed-over tunnels (as distinguished from open slots) the difference will not be so marked. It also makes a great difference whether the magnetic material is laminated or solid. The approach of solid magnetic material affords paths for induced secondary currents, and the inductance will not be increased to such an extent as for correspondingly-situated laminated magnetic material; indeed, in rare cases, the inductance might even be *decreased* by the proximity of suitably-located solid magnetic material. As is well-known,[1] it may be readily decreased by suitably-located *non*-laminated non-magnetic material (such as thick copper slabs).

[1] See British Patents, No. 17,641 (1901), No. 22,035 (1901).

Now, in dynamo-electric machinery the circuits are sometimes completely laminated, as, for instance, in the newer polyphase generators of the Allgemeine Elektricitäts-Gesellschaft,[1] and in induction motors. But in most generators portions of the magnetic circuit exterior to the armature are of solid magnetic material.

For continuous-current generators it has been frequently observed that the presence or absence of the field magnetic circuit was almost without influence upon the value of the inductance of the coils when in the neutral position (*i.e.*, winding between pole-tips). Hence for such machines, measurements as those heretofore described afforded ample data for estimating the reactance of the short-circuited coil. But for alternating-current generators with laminated magnetic cores, the position of maximum inductance has sometimes been found to correspond to that

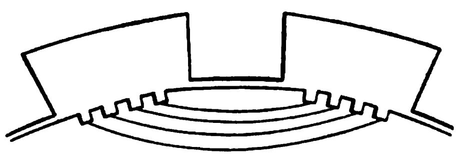


FIG. 532.

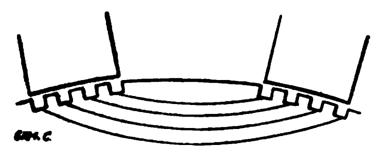


FIG. 533.

DIAGRAMS OF COIL POSITIONS

where the sides of the coils are in the space between pole-tips, *i.e.*, in the position shown in Fig. 532.

This is proof of the presence of a flux set up by the armature currents, penetrating the entire main magnetic circuit, superposed on the local flux around the armature winding, and giving a resultant inductance greater even than that for the conductors when lying directly under the pole-face, *i.e.*, in the position shown in Fig. 533, which latter, owing to the better magnetic circuit afforded to the local flux about the coils, is generally the position of maximum inductance. Hence it is rather difficult to exactly analyse the occurrence, and one finds it most practicable —where the results of observations on a suitable machine are not available —to take a value for the average of the inductance of all positions of the armature. Fig. 533 is much more likely to be the position of maximum, and Fig. 532 that of minimum inductance, the more the magnetic circuit is composed of non-laminated material; because then the flux corresponding to Fig. 532, owing to the generation of secondary currents, cannot so well penetrate around the main magnetic circuit, hence the local flux constitutes

[1] See articles by Herr Lasche in *Engineering*, Vol. LXXII., pages 173, 205, 240, 277.

more nearly the total resultant flux. With non-laminated pole-faces, however, the values of the inductance in the positions shown in Fig. 533 will be smaller than with laminated pole-faces.

To sum up, we have examined into the matter of the relative values —for the armature free in air—of the inductance of surface and slot-wound armatures; the next step is to determine the limiting values for these same windings when in the magnetic field. Let us first take the case of the uni-slot model of Fig. 525, page 470. The magnetic circuit was more or less closed for this model, by approaching to it a magnetic yoke and pole-piece, first to one of laminated iron, and afterwards to one

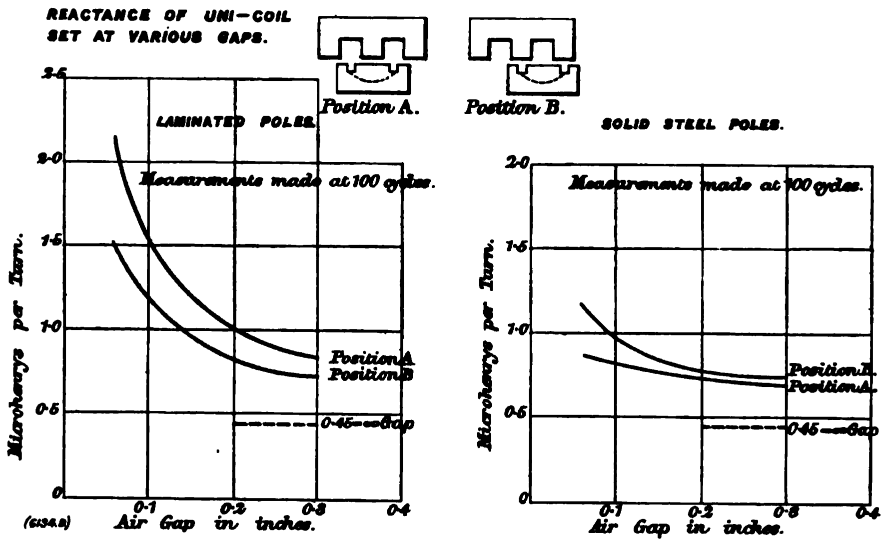


FIG. 534. FIG. 535.

INDUCTANCE CURVES

of solid steel. For the position shown (A and B), the curves of Fig. 534 were obtained for the laminated, and those of Fig. 535 for the solid steel pole-pieces. It is interesting to note :—

(1) The decreased values of the inductances occasioned by the greater opportunity for secondary currents offered by the solid steel pole-pieces.

(2) The interchanged positions of maximum and minimum inductance occasioned by the change in the material of the pole-pieces.

While in this case the position of the slots with reference to the magnetic circuit denoted as position A is that of maximum inductance for the laminated pole-pieces, it is, for the solid pole-pieces, the position of minimum inductance; since, for this latter case, the increased opportunity for eddy-currents decreases very greatly the number of lines which can,

at 100 cycles, penetrate through the main magnetic circuit. Corresponding sets of curves for the multi-coil models are given in Figs. 536 to 543, (see next page); and it is interesting to note that, in all of these cases, the

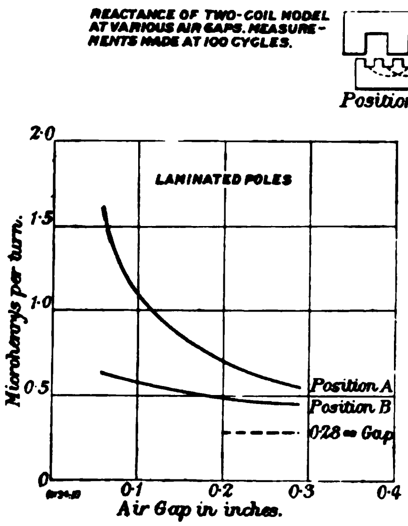


Fig. 536.

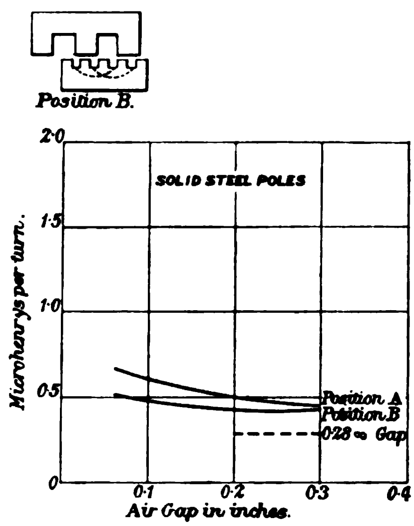


Fig. 537.

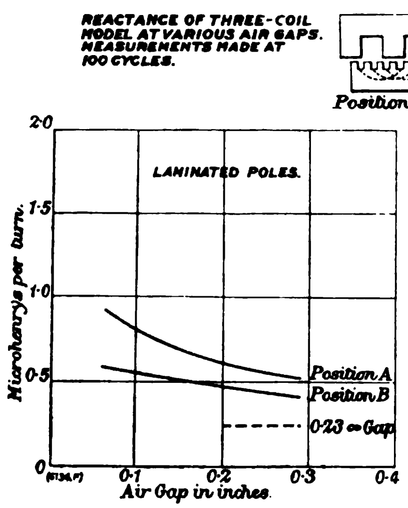


Fig. 538.

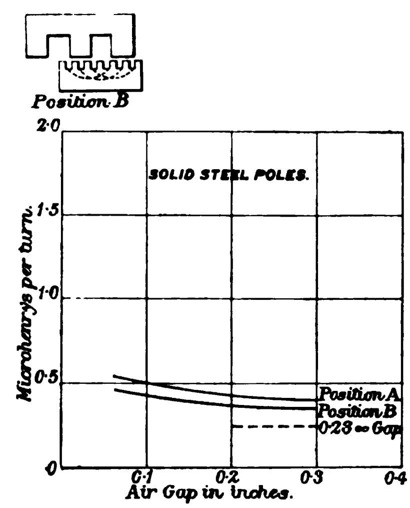


Fig. 539.

Inductance Curves

maximum inductance corresponds to position A, even with the solid steel pole-pieces, instead of, (as in the uni-coil model with solid pole-pieces) to position B. In Fig. 544, on page 477, are given curves of the average value of the inductance for 0.1 in. air gap. Curve I is for the laminated, and Curve II for the solid pole-pieces.

It is thought that this collection of results is very instructive in showing the tendencies exerted by various conditions (such as solid or laminated pole-faces, length of air gap, number of coils, etc.) upon the values of the inductance. But it is very important to point out that the results are only to be employed qualitatively. The models were altogether too different, from the conditions of practice, to yield reliable

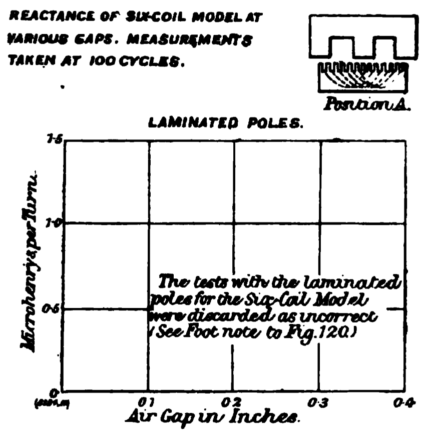


FIG. 540.

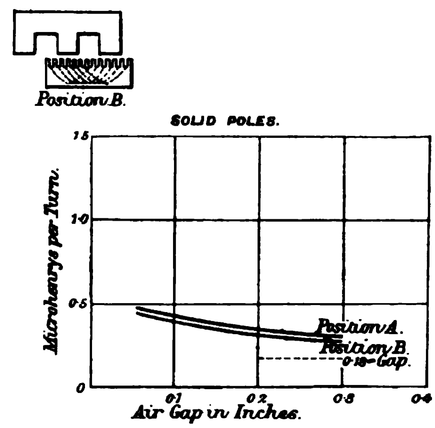


FIG. 541.

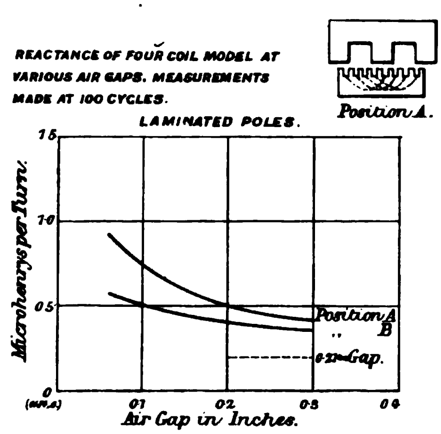


FIG. 542.

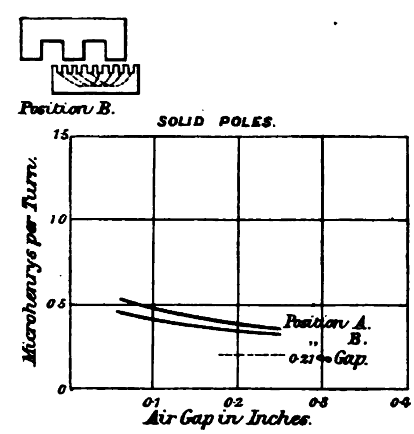


FIG. 543.

INDUCTANCE CURVES

quantitative results. In Fig. 545 are given curves for the inductance, with 0.1 in. air gap, in the position denoted as B, for a 2-pole and for a 3-pole pole-piece, both of the structures being laminated. At first only the 2-pole pole-piece had been provided. The 3-pole pole-piece was also required, because it better corresponded to the conditions of practice in the other position of the models, *i.e.*, that denoted as position A.

The results on the various experimental inductance tests, on coils and on small models, have been given partly in metric units; and this has often been more convenient, since the henry is based upon that system. As, however, we must now return to the consideration of actual machines, it is convenient to tabulate the conclusions, and devote a column to the results as expressed in lines per ampere turn per inch of length, since this conforms with the nomenclature heretofore employed in this work. This is done in Table LXXX., page 478.

Of course, such values are subject to wide variations, and the aim of these tests and tables is merely to assist in developing a capacity to

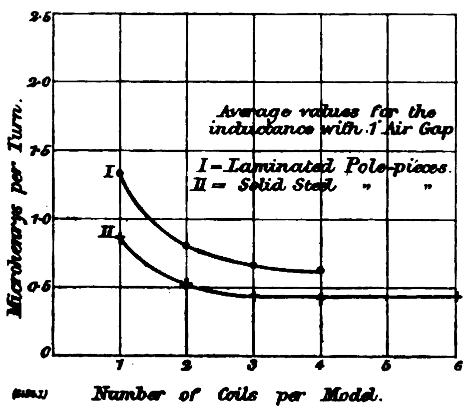


Fig. 544.

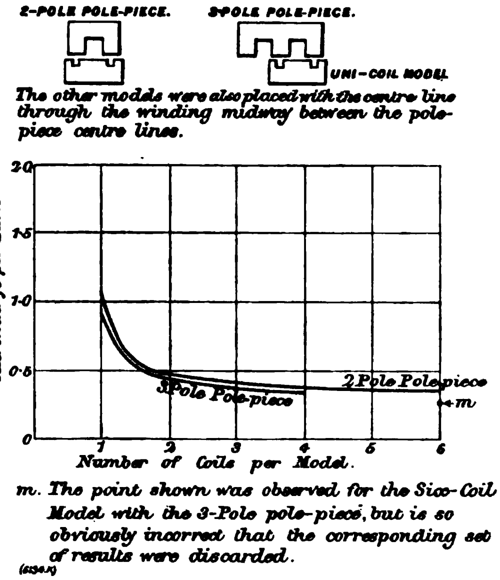


Fig. 545.

Inductances of Test-Model Coils with Laminated and Solid Pole-Pieces

intelligently judge the tendencies of variations in type and proportions, and to arrive at rough estimates of the numerical values.

The derivation of the last column may not be sufficiently evident; the values in the immediately preceding column were doubled because they are there expressed in units of length of embedded winding, whereas the constants, in the last column, are expressed in units length of core. These doubled values were then multiplied by 0.8, since the net length of core ranges generally between 75 per cent. and 85 per cent. of the gross length. The final results were obtained by dividing by 0.6, on the assumption that, for the average proportions, the length between flanges contributes 60 per cent., and the length consisting in end connections the remaining 40 per

cent. of the total inductance. These proportions in practice vary very greatly; nevertheless, it will often be found sufficient, for preliminary approximations, to make use of these rough values; but where an attempt at greater accuracy is thought desirable, the embedded length and the end

TABLE LXXX.—RESULTS OF INDUCTANCE TESTS

Description.	Lines per Ampere Turn per Centimetre of Embedded Length for the Average Inductance.	Lines per Ampere Turn per Inch of Embedded Length for the Average Inductance.	Approximate Values for the Lines per Ampere Turn per Inch of Gross Length of Armature Core between End Flanges for Average Inductance.
Coils laid on laminated surface (coils of small breadth)	2	5	13
Coils laid on laminated surface (coils of breadth equal to pitch) ...	1	2.5	6.5
Uni-coil windings in open, straight-sided slots	3 to 6	7 6 to 15	20 to 40
Thoroughly distributed windings in open, straight-sided slots ...	1.5 to 3	3.8 to 7.6	10 to 20
Uni-coil windings in completely closed-over tunnels	7 to 14	18 to 36	48 to 96
Thoroughly distributed windings in completely closed-over tunnels ...	3 to 6	7.6 to 15	20 to 40

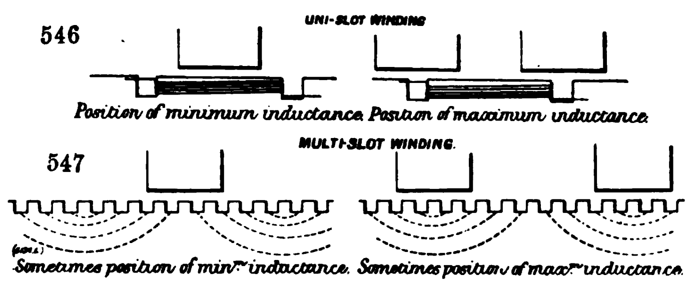
connections may be treated independently, although this takes much more time. Generally the main consideration is to be able to estimate correctly the tendencies of variations in the proportions, and to be able to predetermine approximate limits within which the actual values will fall.

FURTHER CONSIDERATION OF THE INFLUENCE OF THE TYPE OF WINDING, STYLE OF SLOT, AND CONSTRUCTION OF THE MAGNETIC CIRCUIT, UPON THE POSITION OF MAXIMUM INDUCTANCE

From the preceding tests it appears, as has already been briefly mentioned, that whereas in uni-slot alternators there is a very considerable difference between the values of the inductance in the positions of minimum and maximum inductance, this difference diminishes in proportion to the extent of the distribution of the winding; and that with multi-coil windings it is, in fact, often the case that what would be the position of minimum inductance in a uni-slot winding (centre of coil, *i.e.*, midway position maximum between two slots, opposite centre of pole-face) is the position of

inductance in a multi-coil winding. This is clearly illustrated in Figs. 546 and 547.

These considerations show that the inductance depends upon the combined magnetic conductivity to a magnetic flux of the periodicity of reversal of the machine, of two paths, one more or less local, the lines taking a short path around the armature coil, some crossing to the pole face but not extending far from the pole-face surface, and the other following the main magnetic circuit, *i.e.*, flowing through the magnet cores and the connecting yoke. There is, of course, no abrupt distinction to be made between these two sets of lines, the first merges into the second. Obviously, the first class constitutes the greater number, in proportion as the slots are deep, or largely or entirely closed over. The other class will be observed in greater number in low periodicity machines, and in machines with



FIGS. 546 AND 547. DIAGRAMS OF COIL POSITIONS

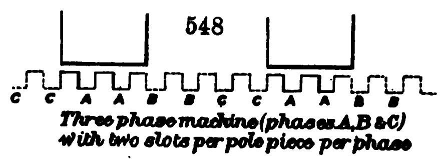
entirely laminated magnetic circuits. Any unlaminated masses in the magnetic circuit, or any closed conductors linked therewith (such as the field-spool flanges in some machines) constitute the seat of opposing magnetomotive forces. This second class of inductance lines has been experimentally observed and measured by exploring coils wound round the yoke. The large proportion which these lines sometimes form of the whole inductance flux is often, at first glance, a source of surprise. The number of lines thus located would be considerably affected by the degree of magnetic saturation of the main magnetic circuit, caused by the constant magnetic flux impressed by the field excitation coils. But in the majority of cases, the total inductance flux is but slightly influenced by the presence of the field excitation, and it is permissible and more convenient to neglect variations from this source in the predetermination of the alternator characteristics.

Inductance of Polyphase Windings

These cannot be treated as mere distributed windings; that is to say, the inductance of a winding with three total slots per pole-piece (one slot per pole-piece per phase) is not to be calculated as if it were a single-phase winding, with three slots per pole-piece, but each of the three phases must be separately handled, and each treated as a uni-slot winding.

Thus, suppose the case of a three-phase machine with two slots per pole-piece per phase (therefore a total of six slots per pole-piece). The three windings are **Y** connected, and the terminal voltage is 2500 volts. The voltage per phase is therefore $\frac{2500}{\sqrt{3}} = 1440$ volts, and the inductance per phase should be estimated as if this one winding alone were present upon the armature, distributed in two slots per pole-piece. But these

548



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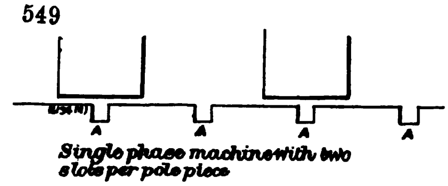


Figs. 548 and 549. Diagrams of Winding Distribution

two slots are not equi-distantly placed on the armature surface, but are close together, with four interposed slots of the other two phases before the next two slots of the first phase come. It is obvious from Figs. 548 and 549 that this state of affairs will lead to a higher value for the inductance than would be the case for a single-phase machine with two equi-spaced slots per pole-piece.

Some tests were made on the experimental models, already shown in Figs. 525 and 529, pages 470 and 471, to illustrate this point.

The results with laminated pole-pieces are given in the curves of Fig. 550, and corresponding results, with cast-steel pole-pieces, are given in Fig. 551. The two sets of curves give a fair idea of the extent of the influences at work, and afford a rough basis for modifying the constants of Table LXXVIII. to apply to the cases of polyphase windings.

Inter-action of the Phases as Affecting the Inductance Values

For the present it will suffice to say that, so far as relates to obtaining the reactance voltage for the purpose of mapping out the characteristics, the inter-action of the phases may be neglected. It has been observed to have but slight quantitative effect, though the nature of the effect is very interesting.

In Fig. 489, Curve B (see page 451), the inductance of the winding of one phase of an 850-kilowatt revolving field three-phase alternator was given, and Curve A of the same figure shows the inductance of one phase

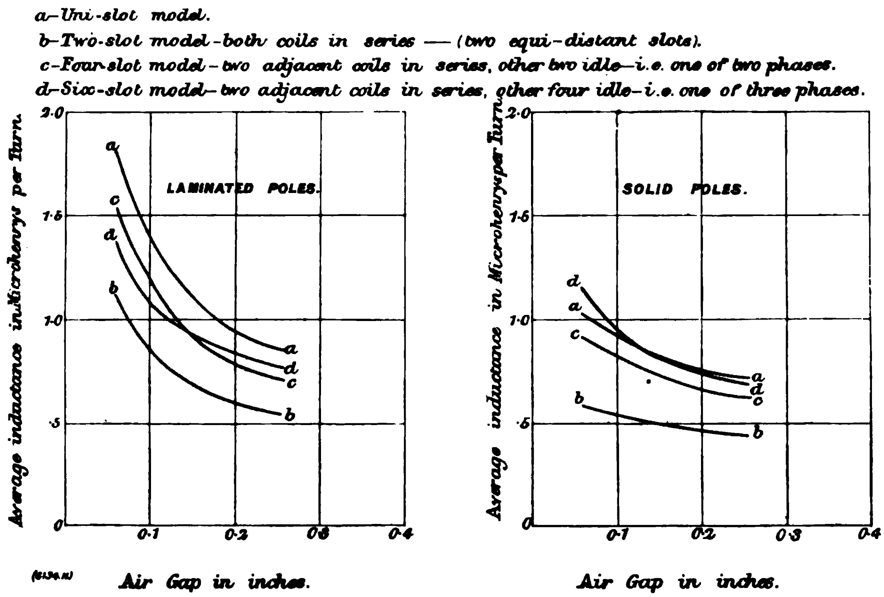


Fig. 550. Fig. 551.

Inductance Tests showing Inter-Action of the Phases

when the windings of the other two phases also carry their corresponding currents. This has had the effect of interchanging the maximum and minimum positions, but has not materially altered the average value of the inductance of one winding.

In general, it may be said that polyphase windings, even more than uni-phase distributed windings, will have much less marked maxima and minima in the inductance values.

The reason why they have such slight effect in modifying the value of the reactance of a single phase is in a general way readily apparent, since the current in each phase successively arrives at its maximum value, and, when at that value, the currents in the other phases are much less,

and, being located in other slots, do not exert much influence on the first phase. In some polyphase windings, conductors of different phases come to be located in the same slot, and in such cases the resultant magnetomotive force should be taken into consideration in deriving the inductance.

The Volt-Ampere Curve and Armature Demagnetisation

It has already been explained that a volt-ampere curve, taken with a given field excitation, will cut the axis of abscissæ at a value of the armature current such that the armature ampere turns per pole-piece are roughly equal to the field ampere turns per pole-piece. This will fail to be the case to the extent that magnetic leakage is present, that is, to the extent that the field turns and the armature turns are, at the instant of maximum value of the wave of armature current, linked with independent magnetic fluxes. Hence, the form of the magnetic circuit in general, and the shape and the type of the armature slots especially, exert considerable influence in determining in how far this equality exists. Moreover, the assumption of a sine wave of current will, when not justified, lead to discrepancies between the observed values and the values predetermined on that assumption.

Table LXXXI.—Showing Range of Variations between Predetermined and Actual Values

Reference number	I.	II.	III.	IV.	V.	VI.	VII.
Number of poles...	8	14	20	10	32	20	20
Rated output in kilowatts	75	120	100	60	300	180	150
Speed, revolutions per minute	900	1070	360	1500	470	750	750
Normal voltage	2300	1150	1150	2300	1150	1150	2300
Periodicity, cycles per second	60	125	60	125	125	125	125
Field spool excitation in ampere turns per pole = a	4000	2900	2875	2900	3650	3250	2950
Number of main slots per pole-piece on armature	1	1	1	1	1	1	1
Turns per pole-piece on armature ...	40	10	12	40	4	12	16
Amperes in armature winding at short circuit with above excitation... ...	80	188	152	45.5	545	320	102
R.M.S. ampere turns per armature pole...	3200	1880	1820	1820	2180	1920	1630
Maximum ampere turns per armature pole (on sine wave assumption) = b ...	4500	2650	2570	2570	3075	2700	2300
$a \div b$	0.89	1.12	1.12	1.16	1.19	1.21	1.29

Although in practice the method is generally amply sufficient, there are given in Table LXXXI. a number of instances of single-phase alternators sufficient to show the range of variation generally occurring in practice between the predetermined and actual values.

In Fig. 552 are sketched, on a reduced scale, the poles and slots corresponding to the above seven cases. These are all uni-slot machines (except that some of them, Cases I., III., and VII., have an intermediate

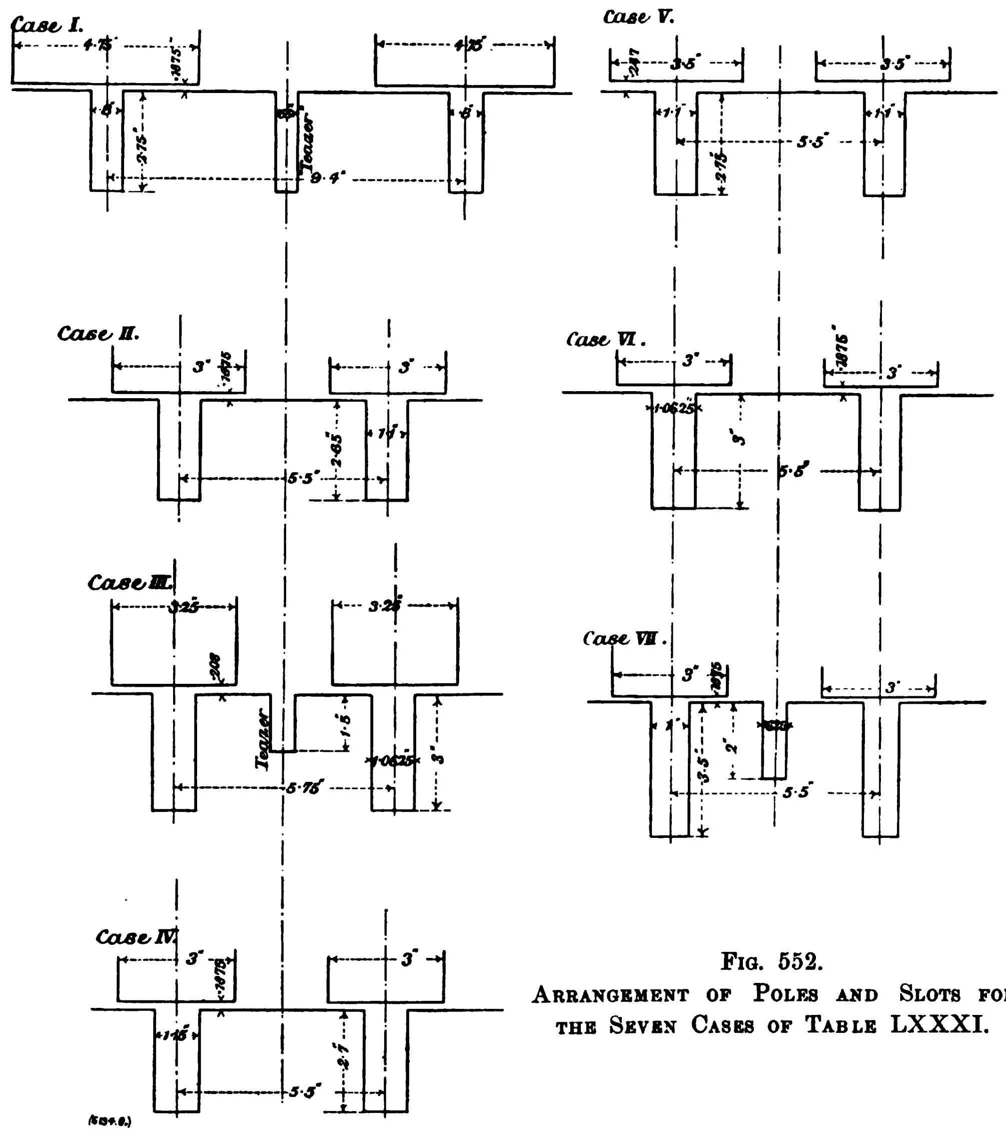


Fig. 552.
Arrangement of Poles and Slots for the Seven Cases of Table LXXXI.

slot, designed to contain an auxiliary winding for feeding motors), and hence would have a wave form in which the ratio of maximum to R.M.S. value is considerably greater than for a sine wave. This would tend toward a value of $\frac{a}{b}$ exceeding unity.

The machines shown in Table LXXXI. and Fig. 552 are rather

old-fashioned, as is almost inevitably the case with single-phase designs. A corresponding analysis for three-phase generators is given in Table LXXXII. and Fig. 553, the Table including instances of machines with one, two, and three slots per pole-piece per phase. The values obtained for the ratio of a to b for the eleven cases ranged between the limits of 1.76 and 2. 43, but ten of them fell between 1.76 and 2.19, the mean value for all the cases being 2.02; thus in none of the ten was there a greater deviation than 13 per cent. from the mean value.

TABLE LXXXII.—SHOWING VALUE OF $\frac{a}{b}$ FOR ELEVEN THREE-PHASE GENERATORS

Reference number ...	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
Number of phases ...	3	3	3	3	3	3	3	3	3	3	3
Connection of phases ...	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Number of poles ...	12	12	6	14	12	20	24	12	12	16	48
Rated output in kilowatts	360	300	225	150	150	75	250	100	150	250	200
Speed, revolutions per minute	600	347	500	514	600	150	125	600	600	450	100
Normal voltage ...	700	3450	6300	2300	2300	3300	5500	2300	3450	2300	300
Voltage per phase ...	404	2000	3630	1330	1330	1900	3180	1330	2000	1330	175
Periodicity, cycles per second	60	35	25	60	60	25	25	60	60	60	40
Field spool excitation in ampere turns per pole $= a$	3550	5255	6750	3400	4100	4800	7850	3950	3850	3800	5300
Number of armature slots per pole-piece per phase	3	2	2	2	2	2	2	1	1	1	2
Armature turns per pole-piece per phase ...	3	16	60	16	14	60	48	21	18	8	3
Amperes per phase at short circuit... ...	480	130	43	81	107	29	56	62	70	154	515
R.M.S. armature ampere turns per pole-piece per phase	1440	2080	2580	1296	1500	1740	2680	1300	1260	1232	1545
Maximum do. on sine wave assumption $= b$	2000	2930	3650	1830	2125	2450	3775	1840	1780	1740	2180
$a \div b$	1.76	1.80	1.85	1.86	1.94	1.96	2.10	2.15	2.16	2.19	2.43

A very interesting point to observe in this Table is the rise in the ratio $a : b$ accompanying the decrease in the number of armature slots per pole-piece per phase, Case XI.[1] being the only exception in this respect. This increase in the ratio is probably mainly due to the more pointed character of the wave with the concentrated windings.

It has already been explained, and diagrammatically illustrated on pages 148 and 149, that the resultant of the magnetomotive forces of three

[1] There is much to indicate that something was wrong with the tests on Case XI.

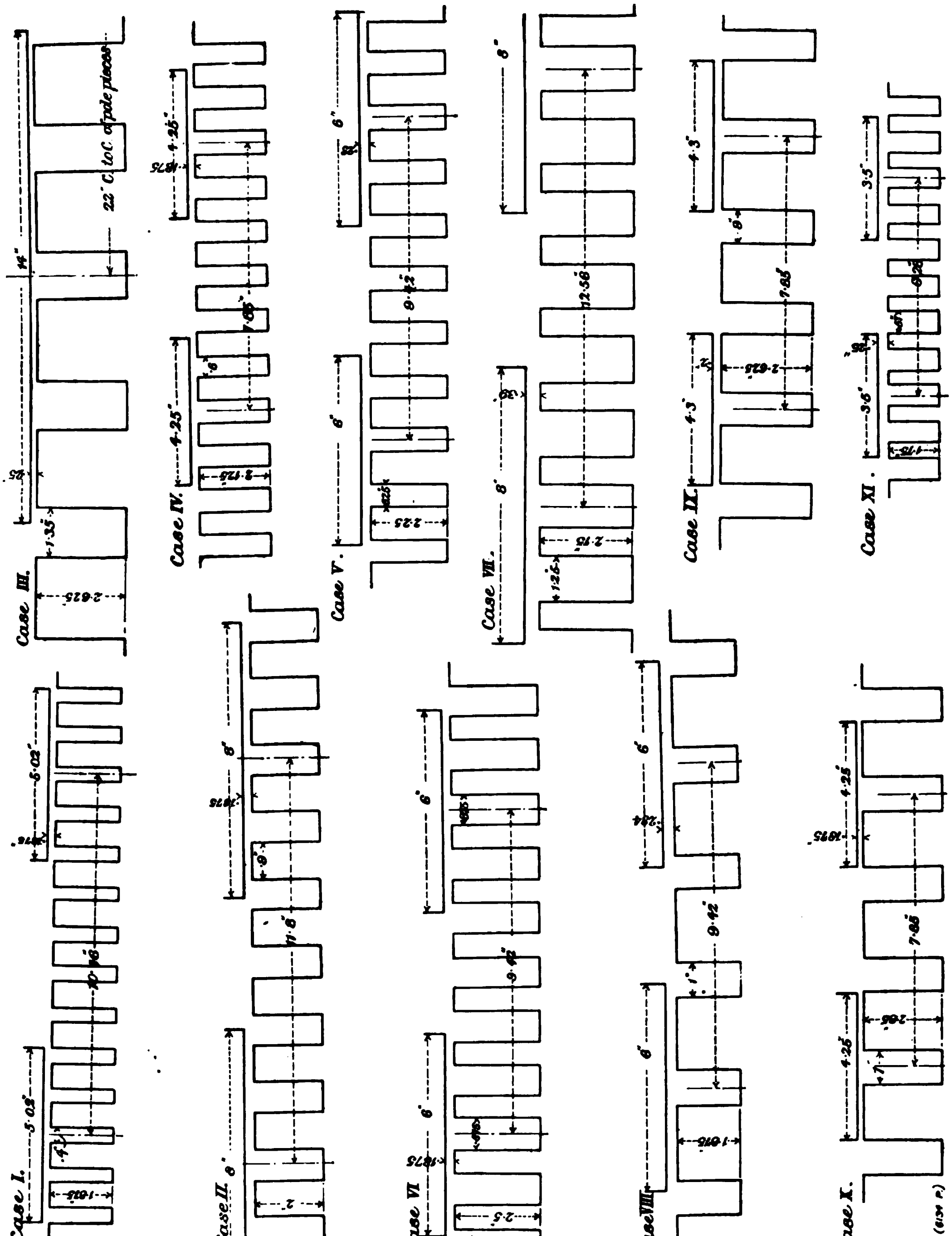


FIG. 553. ARRANGEMENT OF POLES AND SLOTS FOR THE ELEVEN CASES IN TABLE LXXXII.

phases is twice the magnetomotive force of one phase alone for the types of winding used in the generators on which Table LXXXII. is based. Three-phase windings of the types generally employed in rotary converters have been shown, on pages 384 and 385, to have the property that the maximum magnetomotive force, exerted by the armature conductors of all the phases, is, per pole-piece, only 1.73 times as great as the maximum magnetomotive force per pole-piece per phase.

The result for the ordinary winding for three-phase generators, namely, that the resultant magnetomotive force of the armature winding is twice that of the magnetomotive force per phase, may also be shown by other well-known methods; thus Fig. 554 shows the three vectors, each of value unity, combined to the resultant of value 2; and, in fact, in three-phase generators, one arranges the three windings on the periphery, so that the

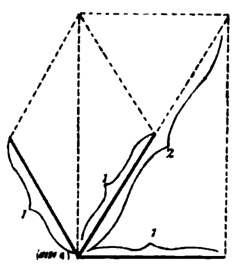


FIG. 554.

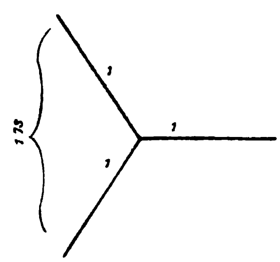


FIG. 555.

VECTOR DIAGRAMS FOR ARMATURE MAGNETOMOTIVE FORCE

electromotive forces generated in them differ from one another by 60 deg. in phase, as shown in Fig. 538, page 475, and, merely by reversing the connections of the intermediate phase, the voltages between the three collector rings become 120 deg. apart in phase, as shown in Fig. 555, the voltage between any pair of collector rings then being, as explained in all elementary text-books, 1.73 times the value of the volts per phase. Fig. 556 illustrates another well-known way of handling the matter. The three sine waves of maximum value 1, drawn in full lines, when combined, form the sine wave shown dotted, which has a maximum value 2.

But all such ways have the fault that, in practice, the waves sometimes depart widely from the sine form, the values of the pole arc and the type of winding exerting wide influences. Very often these influences may with advantage be neglected for preliminary calculations; but one must guard against drawing radically inaccurate conclusions, as would, for

instance, be the case in failing to distinguish between the difference in the resultant magnetomotive forces in windings of the type illustrated in Figs. 419 and 420, on pages 384 and 385, and the more customary windings of the type illustrated in Figs. 153 and 154, on pages 149 and 150.

One of the chief advantages of polyphase over single-phase working lies in the more complete use which can be made of the armature surface by polyphase windings. In single-phase alternators the armature copper cannot be uniformly distributed over the entire armature surface, since this would introduce counter electromotive forces. But the angular spread of the conductors of any one phase of a uniformly-distributed three-phase winding is only 33⅓ per cent. of the polar pitch; consequently the turns of any one

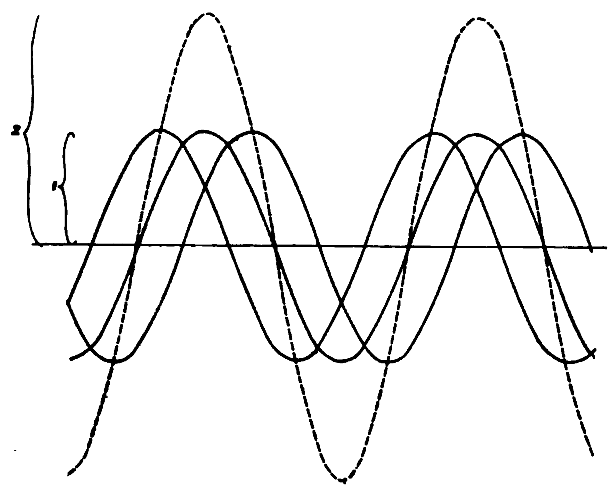


FIG. 556. CURVES FOR COMBINATION OF ARMATURE MAGNETOMOTIVE FORCE

phase are periodically all simultaneously linked with the magnetic flux from the pole-pieces, and as a result are all effectively employed in the production of useful electromotive forces. If the pole-face has a spread of from 60 per cent. to 70 per cent., as will generally be the case, such a uniformly distributed three-phase winding will have about 4.44 for the value of K in the formula—

$$V = KTNM \times 10^{-8},$$

and the electromotive-force curve will be about equivalent to a sine wave, the form factor being about 1.11.

We may, in the case of three-phase dynamos, load the periphery of the armature with 50 per cent. more ampere turns per pole-piece for a given maximum resultant armature strength, than we could in the case of

a single-phase machine. It is not usually deemed desirable to take ful advantage of this; not only would it involve a larger armature C^2R loss, but it is often well to design the machine with a smaller armature strength, as expressed in terms of the resultant armature ampere turns per pole-piece, *i.e.*, twice the armature ampere turns per pole-piece per phase. Good polyphase alternators are characterised, amongst other properties, by the small increase in the field excitation necessary at full load to maintain constant terminal voltage, *i.e.*, by excellent excitation regulation.

While the design of a polyphase alternator, to obtain the best results, will follow along somewhat different lines from that of a single-phase alternator, especially as regards the relative dimensions of armature and field, it may be said in a general way that the expenditure of 100 for active material will give a better result electro-magnetically and thermally in a polyphase alternator than would the expenditure of 120 to 130 in a single-phase alternator.

In a paper read by Mr. M. B. Field before the International Engineering Congress, at Glasgow, on September 5th, 1901, the following very interesting results (see Table LXXXIII.) were given, comprising quotations of cost and weight of three-phase and single-phase generators. The quotations were obtained by Mr. Field from three different makers, especially for the purposes of his paper, and all relate to generators which should comply with the specification accompanying the Table.

TABLE LXXXIII.—COST AND WEIGHT OF 2500-KILOWATT THREE-PHASE AND SINGLE-PHASE GENERATORS; AND THE CORRESPONDING SPECIFICATION TO WHICH THEY COMPLY

	Three-Phase.		Single-Phase.	
	Weight in Tons.	Cost.	Weight in Tons.	Cost.
1	123	£6000	184	£8900
2	120	5400	140	6200
3	110	4600	125	5200

Output, 2500 kilowatts. Voltage, 6500.
Efficiency full load, 96 per cent.
,, three-quarter load, 95 per cent.
,, half load, 93 per cent.
Speed, 75 revolutions. Cycles, 25.
Fall of pressure between full load and no load at constant speed and excitation, and power-factor unity, to be not more than 7 per cent.
Generator to be supplied without outboard bearing or shaft, but with bed-plate rheostat, &c.

With regard to transmitting the current at a given electromotive force between lines and for a given percentage line loss, three-phase transmission effects a saving of 25 per cent. in line copper over that required for single-phase working. This advantage is not possessed by the quarter-phase (commonly called two-phase in this country) system.

It is of special importance in polyphase generators to keep the armature strength and the inductance low, particularly when part or the whole of the load is to consist of lamps on the various branches. For, if in the case of a three-phase generator, for instance, the lamps are unequally distributed on the three branches, there will be an unbalancing of the voltage on these three branches, due to the relative displacement of the phases caused by the different reactance voltages in the three circuits. The *most loaded* branch will have a voltage *intermediate* between the voltages of the other two branches.

Having now obtained an insight into the leading points wherein the design of polyphase machines differs from the design of those for single

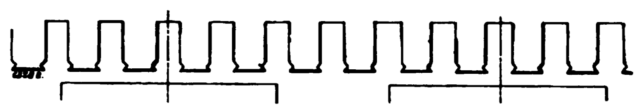


FIG. 557. POLES AND SLOTS OF 150-KILOWATT ALTERNATOR. SCALE 1 : 6

phase, it is proposed to give some curves which were experimentally observed on a three-phase generator ; and then to give, for comparison, the corresponding curves which would have been obtained by calculation from the leading dimensions of the machine.

The machine was of the internal revolving field type. The following brief tabulation includes all the data required for analysing the test results which will be given :—

Rated output	150 kilowatts at unity power factor
Connection of the windings	"Delta"
Terminal voltage	3300
Voltage per phase	3300
Current per phase at full load and unity power factor ...	$\frac{150}{3} \times \frac{1}{3300} = 15.2$ amps.
Speed	500 revolutions per minute
Frequency	50
No. of poles	12

The armature had six slots per pole-piece, and thirty-five conductors in series per slot. The slots were straight-sided and open, with a width of

0.68 in. and a depth of 1.7 ins. A development of the gap and a pair of poles, and the corresponding armature slots, is given in Fig. 557, drawn to scale of 1 : 6.

Depth of air gap	(inches)	0.2
Diameter of armature at gap face	,	40.5
Laminated magnet core and pole-shoe:		
Axial length	,,	11.8
Circumferential width	,,	6.6
Circumferential polar pitch at air gap...	,,	10.6
Axial length of armature between heads	,,	12.2
Effective length	,,	10.0
Mean length of one armature turn	,,	48.5
Armature turns in series per pole-piece per phase		35
(Distributed in two slots per pole-piece per phase)		

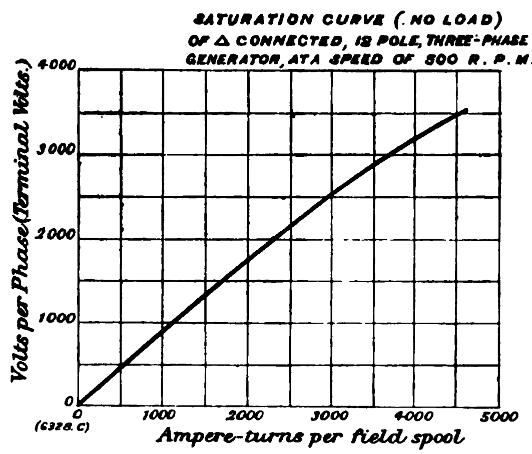
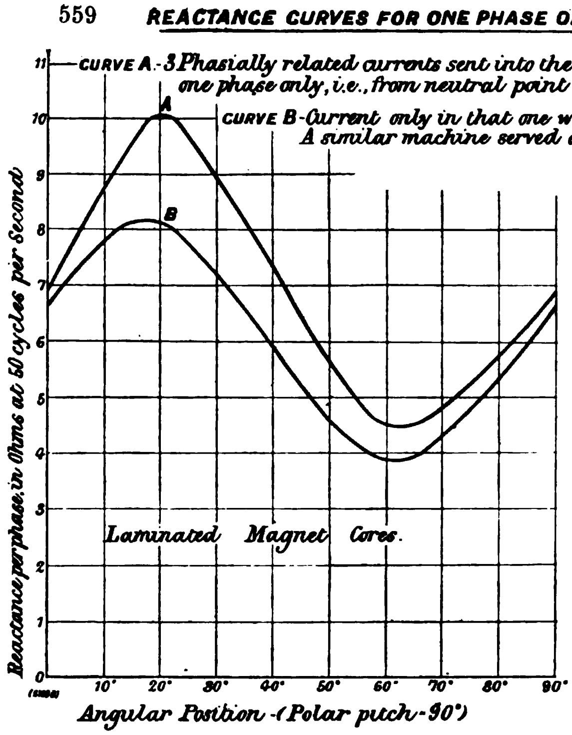


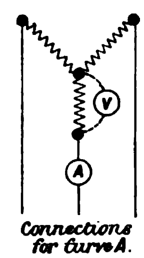
FIG. 558. SATURATION CURVE

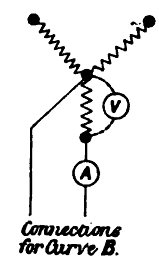
Root mean square armature ampere turns per pole-piece per phase, at full load and unity power factor	530
Maximum armature magnetomotive force per pole-piece *per phase*, ampere turns	750
Maximum *resultant* armature magnetomotive force per pole-piece, ampere turns	1500

The observed no-load saturation curve is given in Fig. 558.

On an identical armature, except that it was wound for 2150 volts at 500 revolutions per minute, and Y-connected with 14 turns in series per pole-piece per phase, the reactance curves shown in Fig. 559 were taken. These curves show the average reactance per phase to be about 7 ohms. The diagrams of connections are given in Figs. 560 and 561.







FIGS. 559 TO 561.

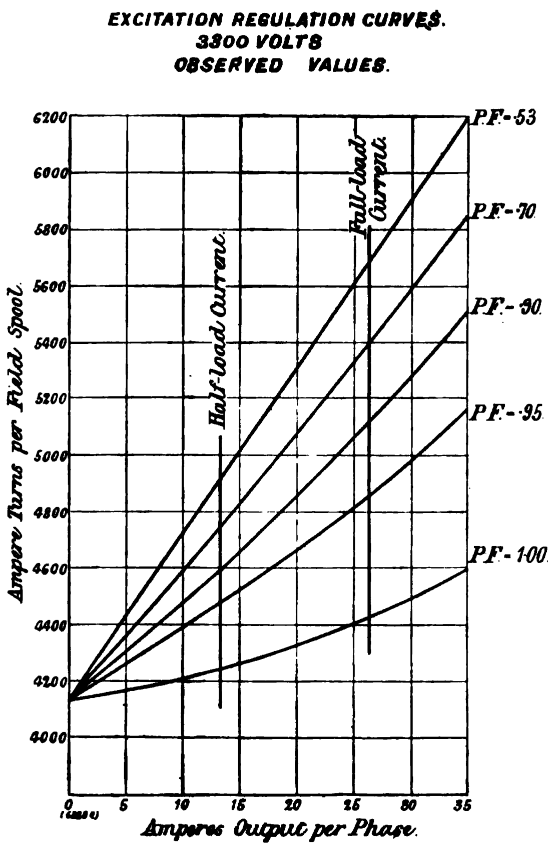


FIG. 562.

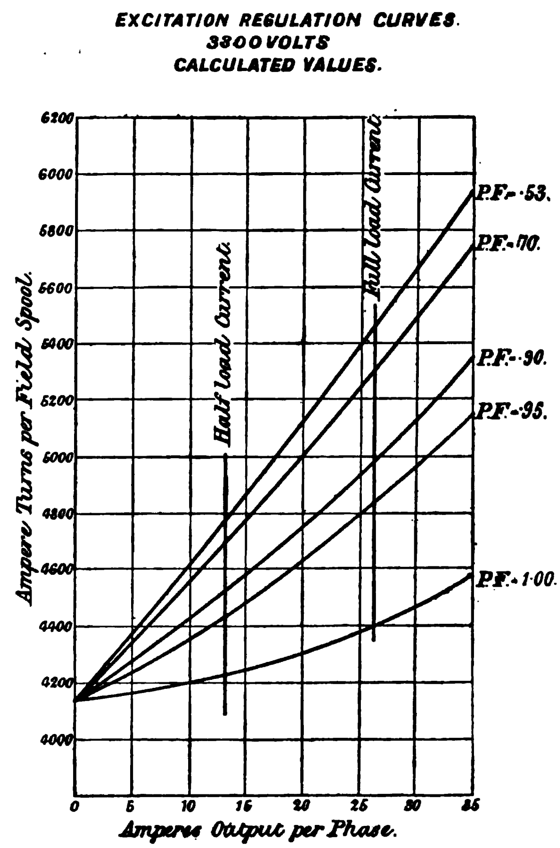


FIG. 563.

For the Δ-connected 3300-volt armature, the reactance per phase would consequently be $\frac{35^2}{14^2} \times 7 = 43.5$ ohms. Hence, for the full-load current of 15.2 amperes, the reactance voltage is $15.2 \times 43.5 = 660$ volts.

In Figs. 562 and 563 are given the observed excitation regulation curves for 3300 volts and various power factors, and corresponding values estimated on the basis of the method already described in these articles.

In Fig. 564 are plotted for full-load and half-load currents, curves representing the required excitation for different power factors of the external circuit. The dotted lines represent the observed and the full

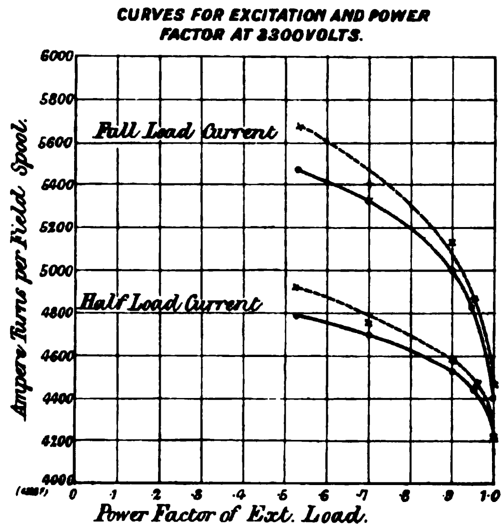


FIG. 564. EXCITATION AND POWER-FACTOR CURVES FOR 150-KILOWATT ALTERNATOR

lines the calculated values, the two sets of curves being derived from Figs. 562 and 563 respectively.

From Fig. 564 it is easy to see that the observed values, while at low power factors distinctly higher than the calculated values, are nevertheless very irregular; and that for all practical purposes the estimated values bear evidence of being a very reliable guide.

DANIELSON'S INDUCTANCE TESTS

In Table LXXX., on page 478, were given values for estimating the inductance in straight-sided slots, and in completely closed-over tunnels. Some very interesting tests, for which the authors are indebted to

Mr. Ernst Danielson, have been made upon partly closed-over slots of two machines of the Allmanna Svenska Aktiebolaget, of Westeras, Sweden.

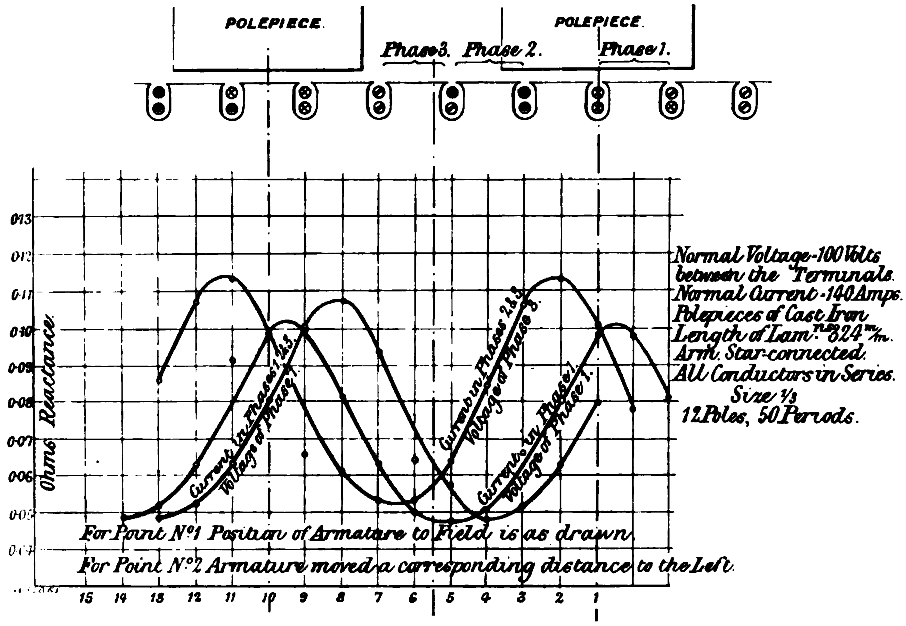


FIG. 565. DANIELSON'S INDUCTANCE TESTS

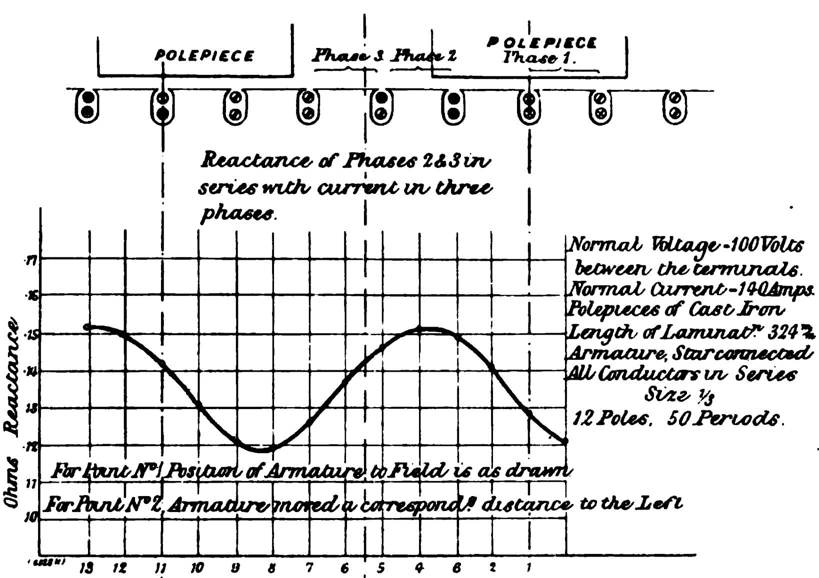


FIG. 566. DANIELSON'S INDUCTANCE TESTS

The test results are set forth in the curves of Figs. 565 to 570.

The average values confirm in the main the values given in Table LXXX., when analysed as intermediary on the one hand between wide

open slots and completely closed-over tunnels; and, on the other hand, as intermediary between concentrated and thoroughly-distributed windings.

A brief analysis will now be given for the average results to be derived from the observations recorded in the curves of these six figures.

Curves of Fig. 565.—For the three curves here given, the reactance was in each case measured from the volts and amperes of one phase, there being for the three cases, current in that phase, in that and another phase, and in all three phases respectively. A reactance of 0.08 ohm is, however, a fair representative value for the results in all three cases. The presence of current in the other phases had but slight effect on the magnitude of the mean result, its principal effect being to shift the position of maximum reactance.

Length of laminations = 324 millimetres (= 12.8 ins.). Consider the winding as made up of six coils of three turns each per phase.

Reactance per three-turn coil $= \frac{0.08}{6} = 0.0133$ ohm; inductance per three-turn coil $= \frac{0.0133}{2\pi \times 50} = 0.0000424$; lines per ampere turn per inch length of laminations $= \frac{4240}{9 \times 12.8} = 36.8$ C.G.S. lines.

Curves of Fig. 566.—These were taken on the same machine. Although the reactance was measured across phases 2 and 3, there were three-phasially related currents in the three windings. Hence, the reactance of one phase is equal to the mean reactance 0.135 ohm divided by $\sqrt{3}$; hence, mean reactance per phase = 0.078 ohm.

This is in close agreement with the result for the curves of Fig. 565.

Curve of Fig. 567.—In this case, again on the same machine, a single current was sent through phases 2 and 3 in series; hence the reactance for one phase equals one-half of the mean reactance, or $\frac{0.168}{2} = 0.084$ ohm, also in close agreement with the results for Figs. 565 and 566.

Curve of Fig. 568.—Here the tests were made upon a machine with 6 coils per phase and 12 turns per coil; length of laminations = 380 millimetres = 15 in.; mean reactance per phase = 1.20 ohms; reactance per 12-turn coil = 0.200 ohm; inductance per 12-turn coil $= \frac{0.200}{2\pi \times 50} =$ 0.000635; lines per ampere turn per inch length of laminations $= \frac{63{,}500}{144 \times 12.8} = 34.5$ C.G.S. lines.

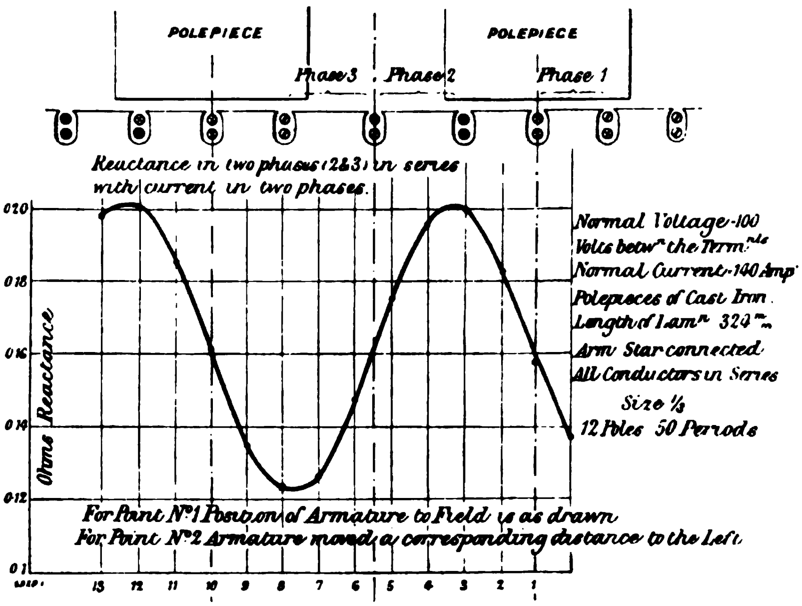


Fig. 567. Danielson's Inductance Tests

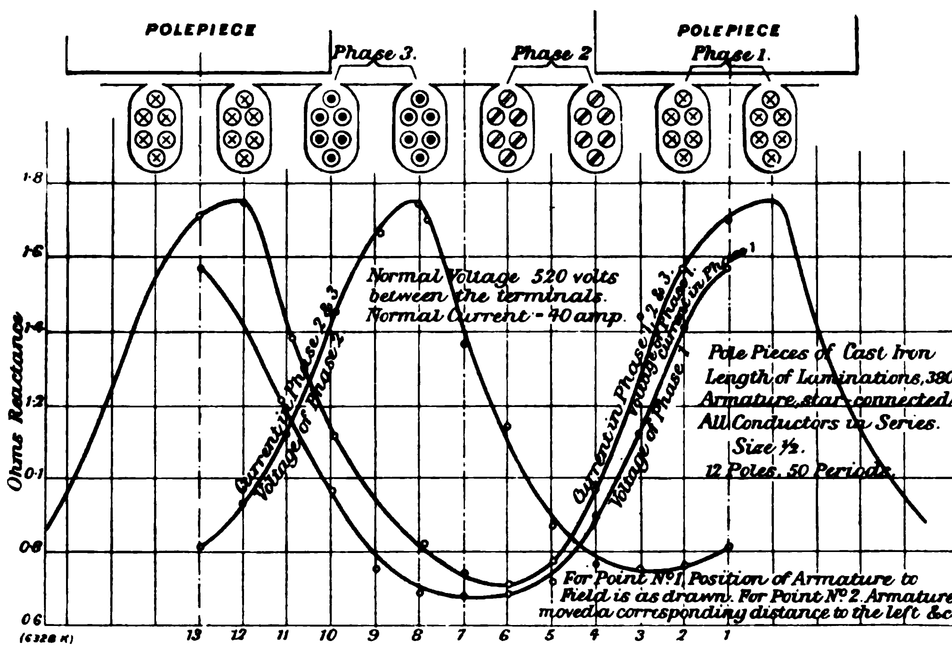


Fig. 568. Danielson's Inductance Tests

Curve of Fig. 569.—For this curve, which was made on the same machine, measurements were made across two phases, but with three-phasially related currents in the three windings: mean reactance across

two phases = 2.02 ohms; mean reactance per phase = $\frac{2.02}{3}$ = 1.17 ohms, practically the same result as for the preceding figure.

Curve of Fig. 570.—In this case, again on the same machine, a single current was sent through the windings of two of the phases in series, and the corresponding voltage measured: mean reactance across two phases = 2.18 ohms; mean reactance per phase = 1.09 ohms, this being 8 per cent. less than the mean results from the tests of Figs. 568 and 569.

The result should be less, since this last case is practically that of a four-slot single-phase winding, the four slots being distributed over two-thirds of the circumferential pitch.

Herein is to be noted a slight lack of consistency with the results of the tests on the other machines recorded in Figs. 565 to 567, and for which the curve of Fig. 567 should have shown a corresponding decreased reactance per phase as compared with the results from the curves of Figs. 565 and 566. However, it is only a matter of a few per cent.; the results of this whole group of tests are, in the main, remarkably uniform. It is important to notice that both of these machines had cast-iron pole-pieces, since this construction exerts a marked influence to cause the position of maximum inductance to tend to approach that where the slots containing the windings on which the inductance is measured are directly under the pole-face. The effect of the currents in the neighbouring phases in shifting this position of maximum inductance, is one of the most interesting features of these two sets of tests.

In Table LXXX. the following approximate values were given for the "lines per ampere turn per inch of gross length of armature core, corresponding to the average inductance."

Uni-coil windings in open straight-sided slots	20 to 40
Mean value	30
Uni-coil windings in *completely* closed-over tunnels	48 to 96
Mean value	72
Hence, uni-coil winding in *partly* closed-over slots = $\frac{30 + 72}{2}$ =	51
Thoroughly distributed windings in open straight-sided slots ...	10 to 20
Mean value	15
Thoroughly distributed windings in *completely* closed over tunnels	20 to 40
Mean value	30
Hence, thoroughly distributed windings in *partly* closed-over slots = $\frac{15 + 30}{2}$ = ...	22.5

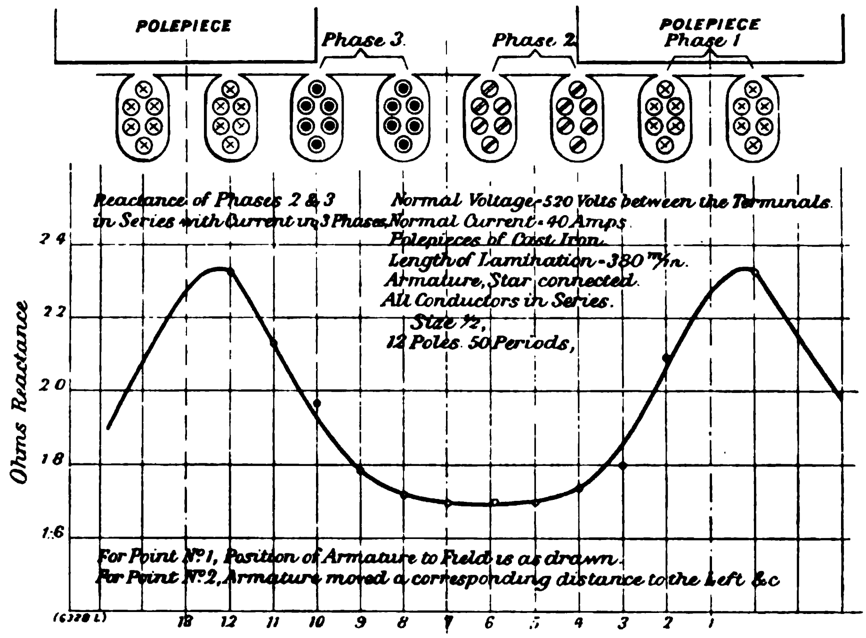


FIG. 569. DANIELSON'S INDUCTANCE TESTS

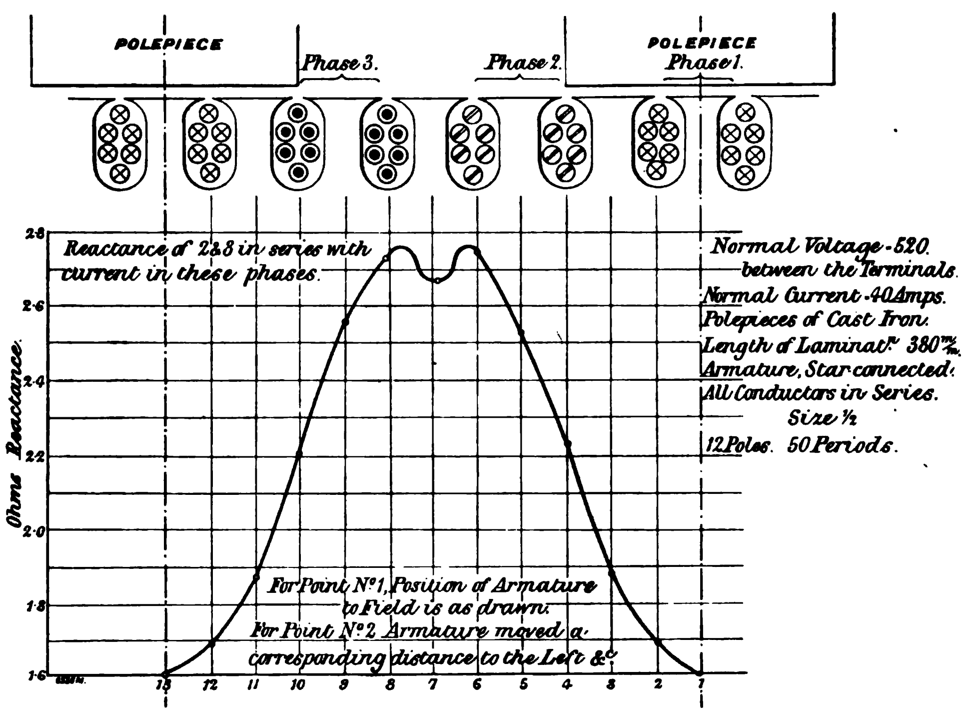


FIG. 570. DANIELSON'S INDUCTANCE TESTS

Hence, for *partly* distributed windings in *partly* closed-over slots could be given the rough representative value of $\frac{51 + 30}{2} = 40.5$ lines.

As a matter of fact, the tests just analysed for two such machines gave the values of 36.6 and 34.5. But, of course, such close agreement is largely chance. The range of values might be usefully taken as from 30 to 50 lines for *partly*-distributed windings in *partly*-closed-over slots.

A few more thoroughly careful sets of tests on machines of varied proportions and style of construction would go far towards obtaining a good working basis for these inductance values.

Description of a 40-Pole, 2500-Kilowatt, Three-Phase, 25-Cycle, 6,500-Volt, 75 Revolutions per Minute Revolving Field Alternator

Four of these alternators, coupled, two of them to Allis and two to Musgrave engines, are employed in the power-house of the Glasgow Corporation Tramways, a view of which is given in Fig. 571, Plate VI. They were built at the Schenectady Works of the General Electric Company of America. The construction and the leading dimensions are shown in the drawings in Figs. 572 to 579, page 499, and Figs. 580 to 582, page 501. A technical specification is given in Table LXXXIV.

Table LXXXIV.—Glasgow 2500-Kilowatt Generators (Revolving Field Type)

Rated output	2500 kilowatts
Number of phases	3
Connection of phases	Y
Periodicity in cycles per second	25
Speed in revolutions per minute	75
Voltage between terminals	6500
,, per phase	3750
Amperes per phase	222
Number of poles	40
Data for Armature Iron:	
External diameter of armature laminations	220 in.
Diameter at the bottom of the slots	$207\frac{1}{4}$,,
Internal diameter of armature laminations	200 ,,
Gross length of core between flanges	22 ,,
Number of ventilating ducts	7
Width of each ventilating duct	$\frac{1}{2}$ in.
Per cent. insulation on core plates	10
Effective length of armature core	16.6 in.
Number of slots	240
,, per pole per phase	2

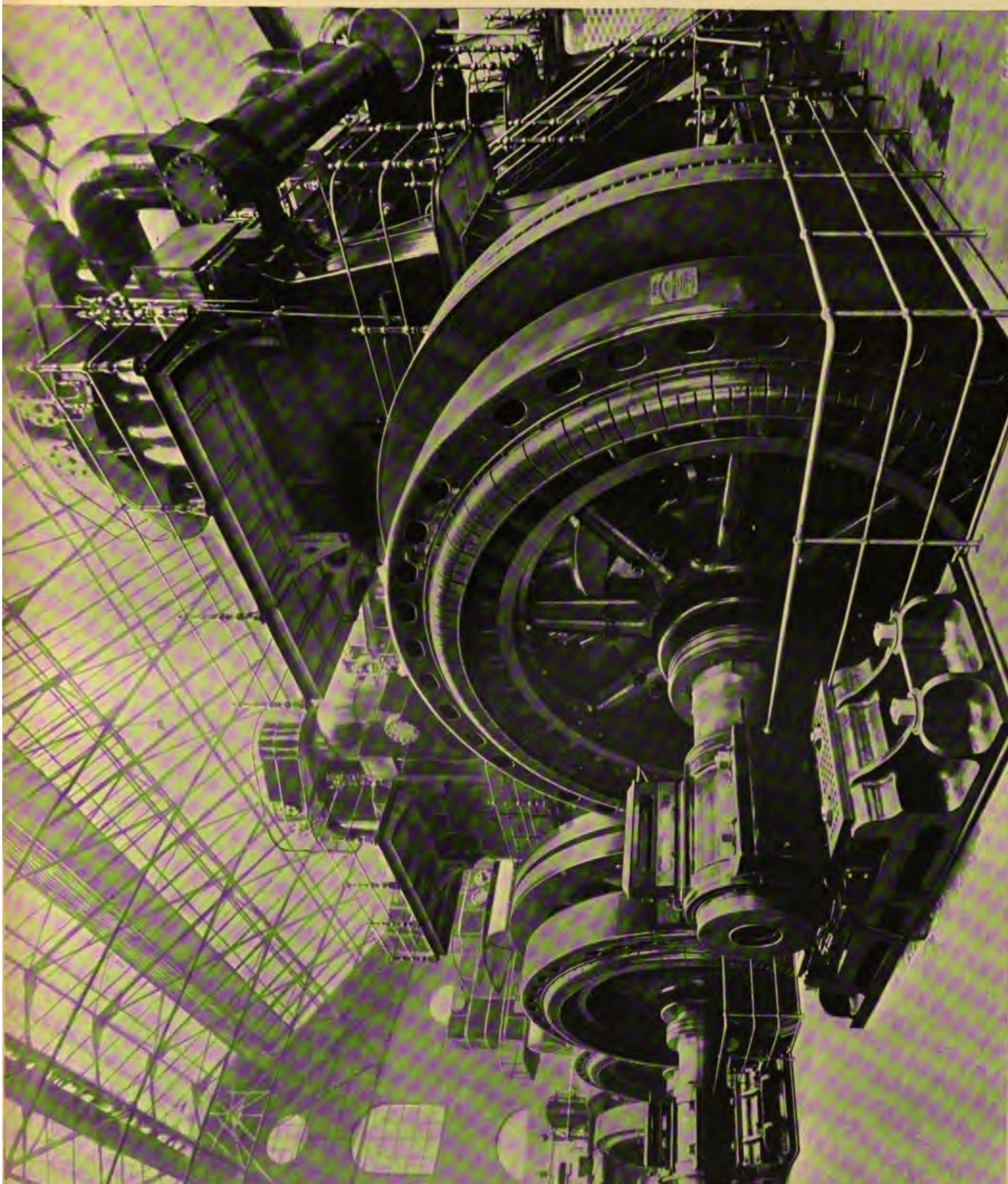


FIG. 571. 2500-KILOWATT ALTERNATORS AT THE GLASGOW TRAMWAYS POWER HOUSE

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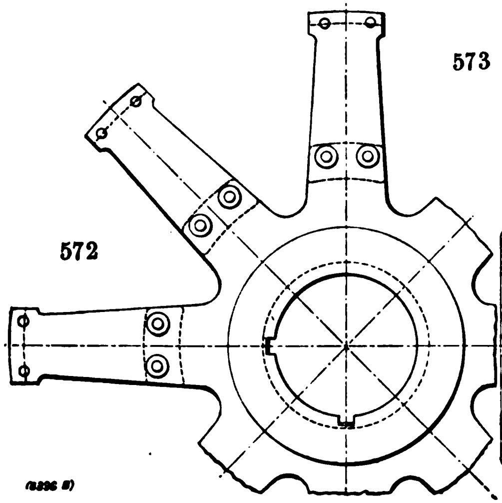

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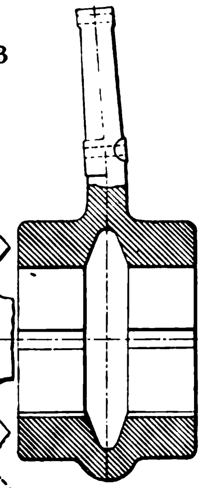

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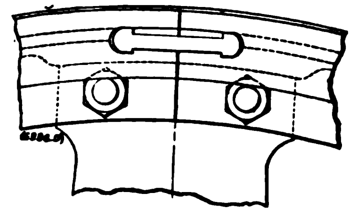

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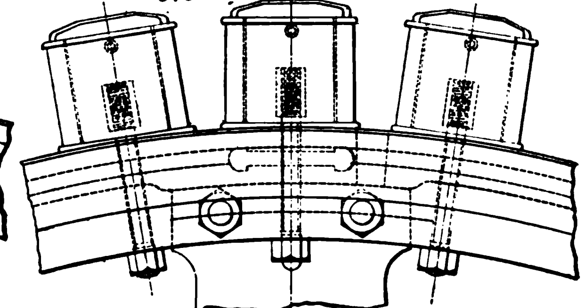

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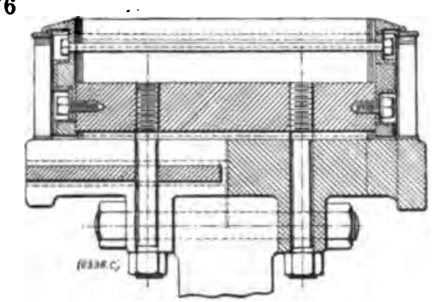

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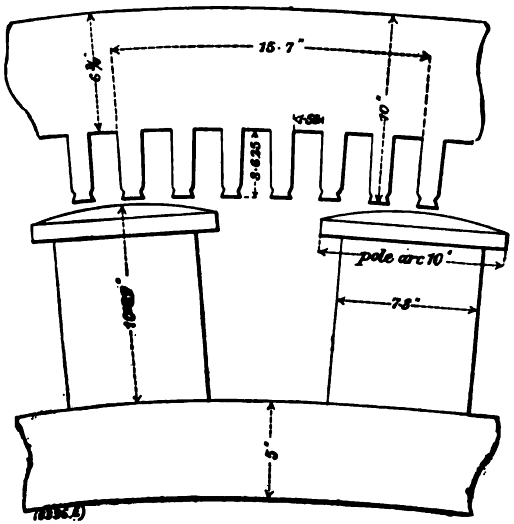

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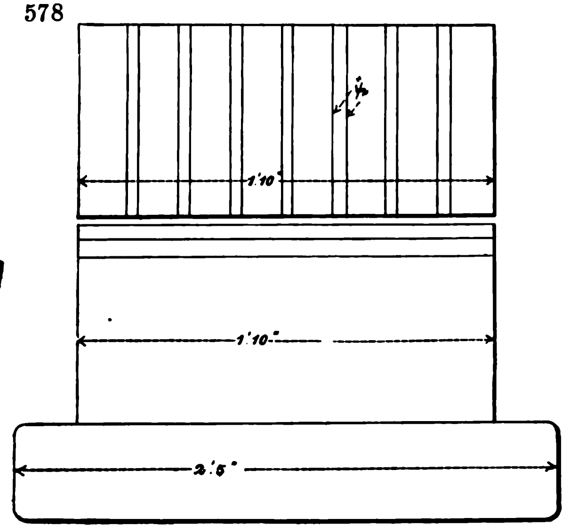

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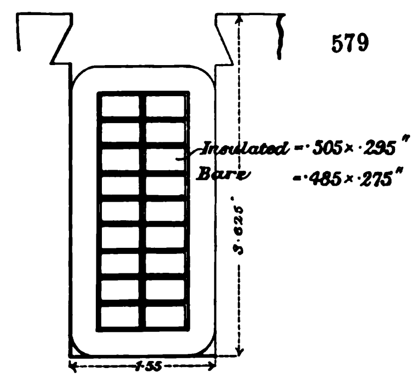


FIGS. 572 TO 579. DETAILS OF ALTERNATORS, GLASGOW CORPORATION TRAMWAYS

Width slot plus tooth at bottom of slot	2.70 in.
„ „ armature face	2.62 „
Depth of slot	$3\frac{5}{8}$ „
Width of slot[1]	1.55 „
„ tooth at armature face	1.07 „
„ „ root	1.15 „
Net weight of armature laminations after deducting slots	25,000 lb.

Dimensional Data for Revolving Field:

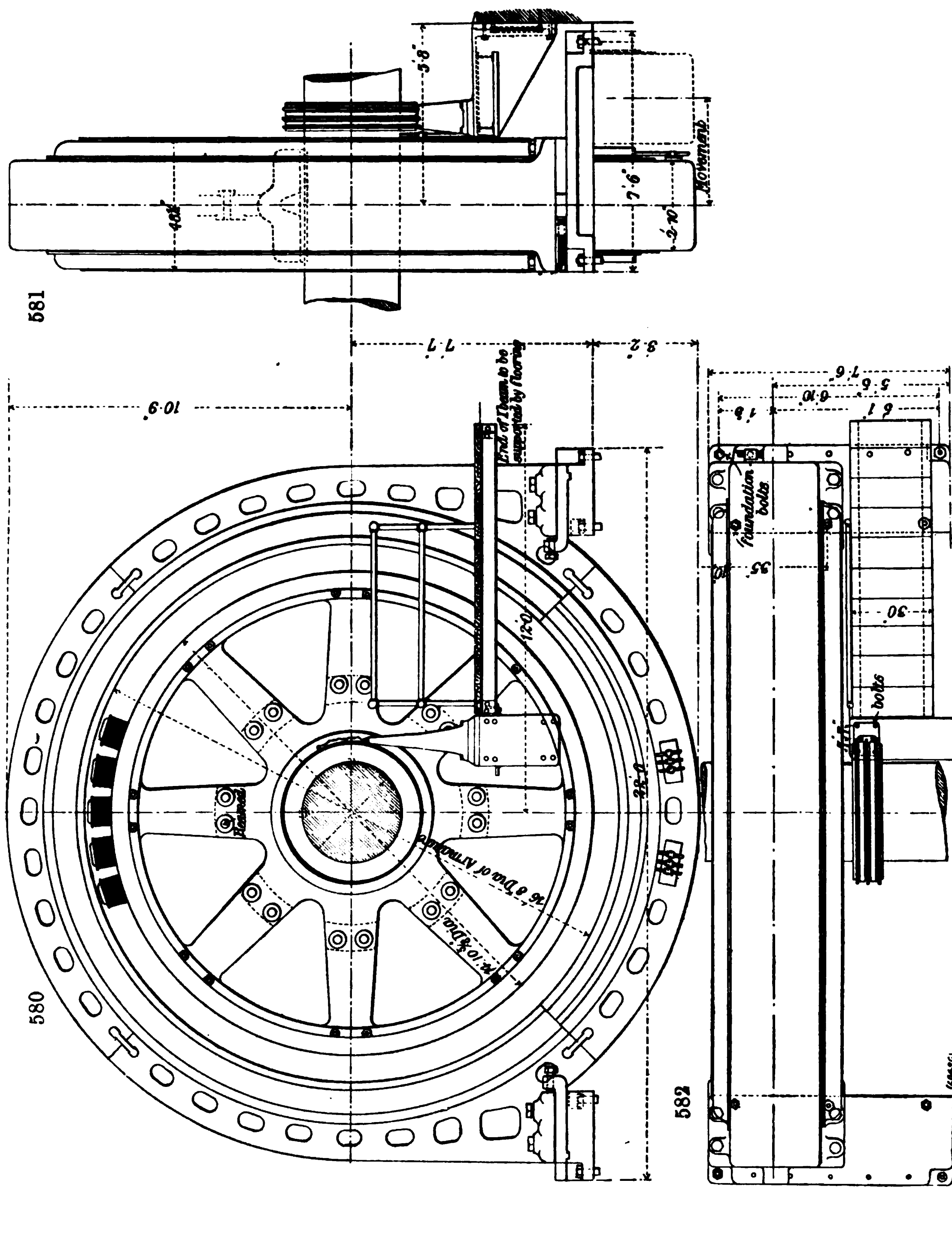
Radial depth of the air gap at the middle of the pole arc	$\frac{5}{16}$ in.
Average radial depth of air gap	0.4 „
Pole-face diameter	$199\frac{3}{8}$ „
Diameter at bottom of magnet core	$178\frac{5}{8}$ „
Total radial length of magnet core, including pole-shoe	$10\frac{3}{8}$ „
Radial length available for spool winding	$8\frac{3}{4}$ „
Material of magnet core	Laminations
Material of yoke	Cast iron
Polar pitch at air gap	$15\frac{3}{4}$ in.
Length of pole arc	10 „
Ratio of pole arc to pitch	0.64
Length pole-shoe parallel to shaft	22 in.
Cross-sectional dimensions of magnet core	22 in. × 7.3 in.
Internal diameter of yoke	$158\frac{5}{8}$ in.
Cross-sectional dimensions of yoke	29 in. × 5 in.
Weight of magnet cores (including pole-shoes)	19,200 lb.
Weight of yoke (exclusive of spider)	23,000 „

Data of Armature Copper:

Number of conductors per slot (2 in parallel)	18
„ slots	240
Total number of conductors	4320
Turns in series per phase, T	360
Arrangement of conductors in a slot	2 × 9
Material of conductor	Pressed cable
Size „	0.485 in. × 0.275 in.
Dimensions when insulated	0.505 in. × 0.295 in.
Insulation from copper to iron	0.28 in.
Apparent cross-section of two conductors in parallel	0.266 square inch
True cross-section one conductor (75 per cent. of apparent cross-section)	0.200 „
Mean length of one turn	97 in.
"Effective" length per turn	33.2 „
"Free" „ „	63.8 „
Resistance of armature winding per phase at 60 deg. Cent.[2]	0.14 ohm.
Weight of armature copper	7000 lb.

[1] The slot is wide open, *i.e.*, it is the same width from bottom to armature face.

[2] The winding consists of 120 coils (40 per phase) in 240 slots. Each coil contains 9 turns, and each turn consists of two conductors, each conductor measuring 0.485 in. wide × 0.275 in. deep.



FIGS. 580 TO 582. DETAILS OF ALTERNATORS, GLASGOW CORPORATION TRAMWAYS

Data of the Magnet Copper:

Number of turns per spool	42.5
Size of conductor	$1\frac{5}{8}$ in. × 0.17 in.
Total resistance at 60 deg. Cent.	0.29 ohm.
Number of spools in series	40
Resistance per spool at 60 deg. Cent.	0.0073
Exciter voltage	100
Mean length of one field turn	64 in.
Total weight of copper in 40 spools	10,000 lb.

The ampere turns at no-load are shown in the no-load saturation curve of Fig. 583.

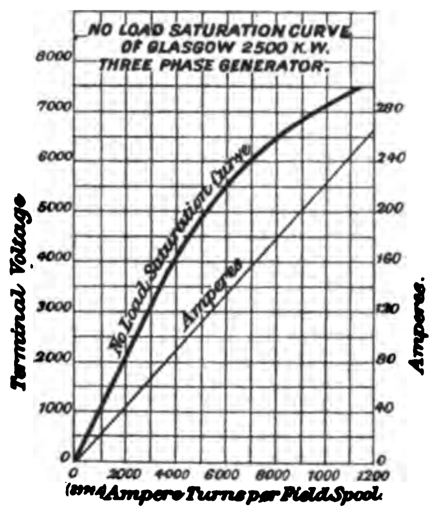


FIG. 583. NO-LOAD SATURATION CURVE

The terminal voltage is 6,500. The volts per phase are 3750 volts. Letting M = magnetic flux at no-load and 3750 volts per phase, then—

$$3750 = 4.00 \times f^* \times 360 \times 25 \times M \times 10^{-8}$$

For this machine f = 1.25, and

$$M = \frac{3,750,000,000,000}{4 \times 1.25 \times 360 \times 25} = 8,350,000.$$

The leakage coefficient = 1.3. The flux in magnet frame = 1.3 × 8.35 = 10.8 megalines.

The cross-sections and densities at no load and 3750 volts per phase are as follows :—

* f = form factor. For Tables of values of f, and for general discussion of the subject of the calculation of the no-load electromotive force of alternators, see pages 82 to 93.

	Cross-Section in Square Centimetre.	Density in Lines per Square Centimetre.
Armature core	1,370 ...	6,100
,, teeth	500 ...	16,700
Pole-face	1,420 ...	5,900
Magnet core	1,040 ...	10,400
Yoke	1,870 ...	5,800

The full-load output per phase $= \dfrac{2,500,000}{3} = 833,000$ watts, and the full-load current per phase $= \dfrac{833,000}{3750} = 222$ amperes.

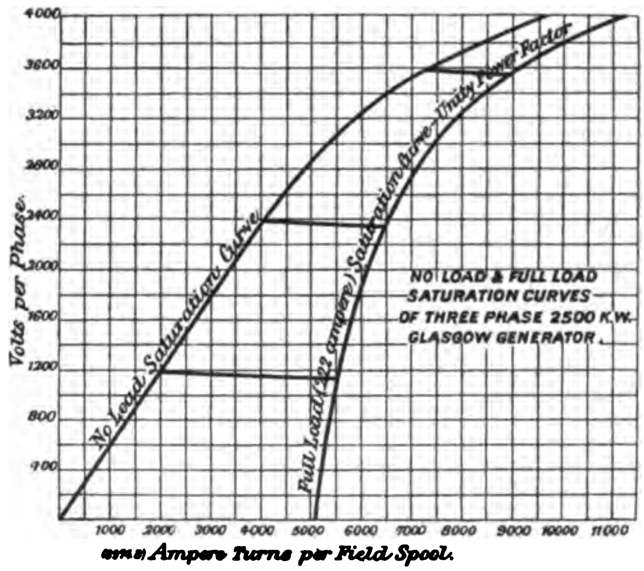


FIG. 584. NO-LOAD AND FULL-LOAD SATURATION CURVES

To send 222 amperes through the short-circuited armature, it was found by test that an excitation of 5100 ampere turns per field spool was necessary. On the armature there are 360 turns in series per phase, or 9 turns per pole per phase, and at 222 amperes there are $9 \times 222 \times \sqrt{2} = 2830$ ampere turns. The resultant for the three phases is $2 \times 2830 = 5660$ ampere turns, or 11 per cent. higher than the observed field excitation necessary for 222 amperes per phase on short circuit.

DETERMINATION OF THE INDUCTANCE FROM THE SATURATION CURVES

The inductance of this machine was not measured. Saturation curves were, however, taken at no-load, and at 222 amperes per phase and unity power-factor. These two curves are given in Fig. 584, plotted in terms of

the volts *per phase*. From them we may derive the inductance. We shall make independent calculations of the inductance, working from three points on the no-load saturation curve of Fig. 584, namely, 1200, 2400, and 3600 volts per phase. The I R drop per phase is, for 222 amperes, $0.14 \times 222 = 31$ volts.

Therefore, the corresponding voltages on the full-load saturation curves of Fig. 584 are:

1169, 2369, and 3569 volts.

Voltage per phase	1200 ...	2400 ...	3600
Excitation at no-load (ampere turns) ...	2000 ...	4050 ...	7400
" 222 amperes and cos. $\phi = 1$ ...	5500 ...	6500 ...	8909

The difference between these two excitation values equals the ampere turns required for overcoming armature demagnetisation.

Ampere turns required for overcoming armature demagnetisation	3500 ...	2450 ...	1500

The total armature strength, by calculation, is equal to $9 \times 222 \times \sqrt{2} \times 2 = 5660$ ampere turns. But from the 222-ampere saturation curve, it is seen that the test value is 5100 ampere turns. Let θ = angle of displacement of maximum current behind mid-pole face position, then we have for the three cases:—

5,100 sin θ equals	3,500 ...	2,450 ...	1,500
Sin θ	0.685 ...	0.480 ...	0.294
Tan θ	0.940 ...	0.548 ...	0.323

Tan θ is the ratio of the reactance voltage per phase to the main voltage per phase; hence in these three cases is respectively equal to:—

$$\frac{\text{R.V.}}{1200}, \frac{\text{R.V.}}{2400} \text{ and } \frac{\text{R.V.}}{3600}.$$

Therefore, R.V. at 222 amperes equals 1130, 1320, and 1170. From this point we shall work from the mean value of the reactance voltage thus deduced. Reactance voltage per phase at 222 amperes equals

$$\frac{1130 + 1320 + 1170}{3} = 1210 \text{ volts.}$$

Reactance $= \frac{1210}{222} = 5.50$ ohms. $5.50 = 2 \times \pi \times 25 \times l$. Where l equals the inductance of one phase in henrys, $l = 0.0350$ henry.

The winding of each phase consists of twenty 18-turn coils in series—

$\therefore$ Inductance of one 18-turn coil $= \frac{0.0350}{20} = 0.00175$ henry.

Lines per ampere turn $= \frac{175{,}000}{18^2} = 540.$

Lines per ampere turn per inch gross length of armature lamination $= \frac{540}{22} = 24.6$

From the value of the reactance per phase (5.50 ohms), and the no-load saturation curve, we may—as we have already shown for other cases—calculate the performance of this machine under all circumstances.

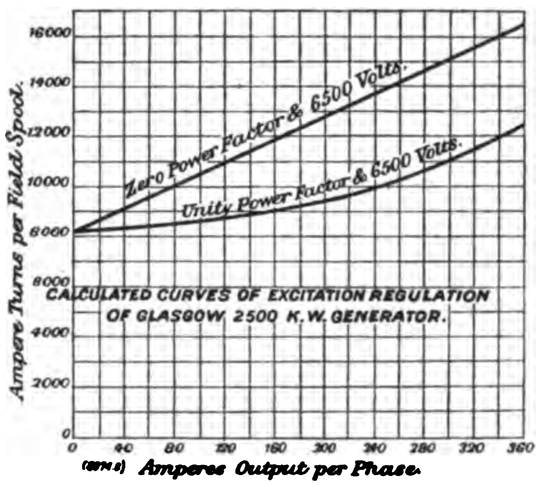


FIG. 585. EXCITATION REGULATION CURVES

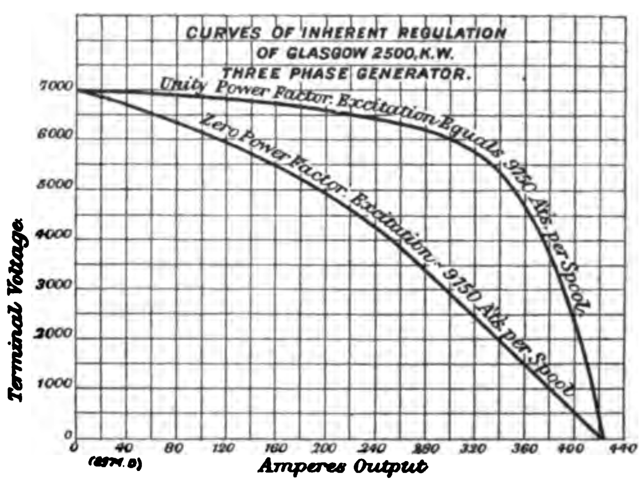


FIG. 586. INHERENT REGULATION CURVES

Curves of its excitation regulation for 6500 terminal volts, and for unity and zero power-factor, are given in Fig. 585. Curves of the inherent regulation for 9750 ampere turns per field spool are given in Fig. 586. The variation of the excitation with the power-factor is shown in Fig. 587. Curves of losses and efficiency are given in Figs. 588 and 589 (page 507).

Fig. 594.

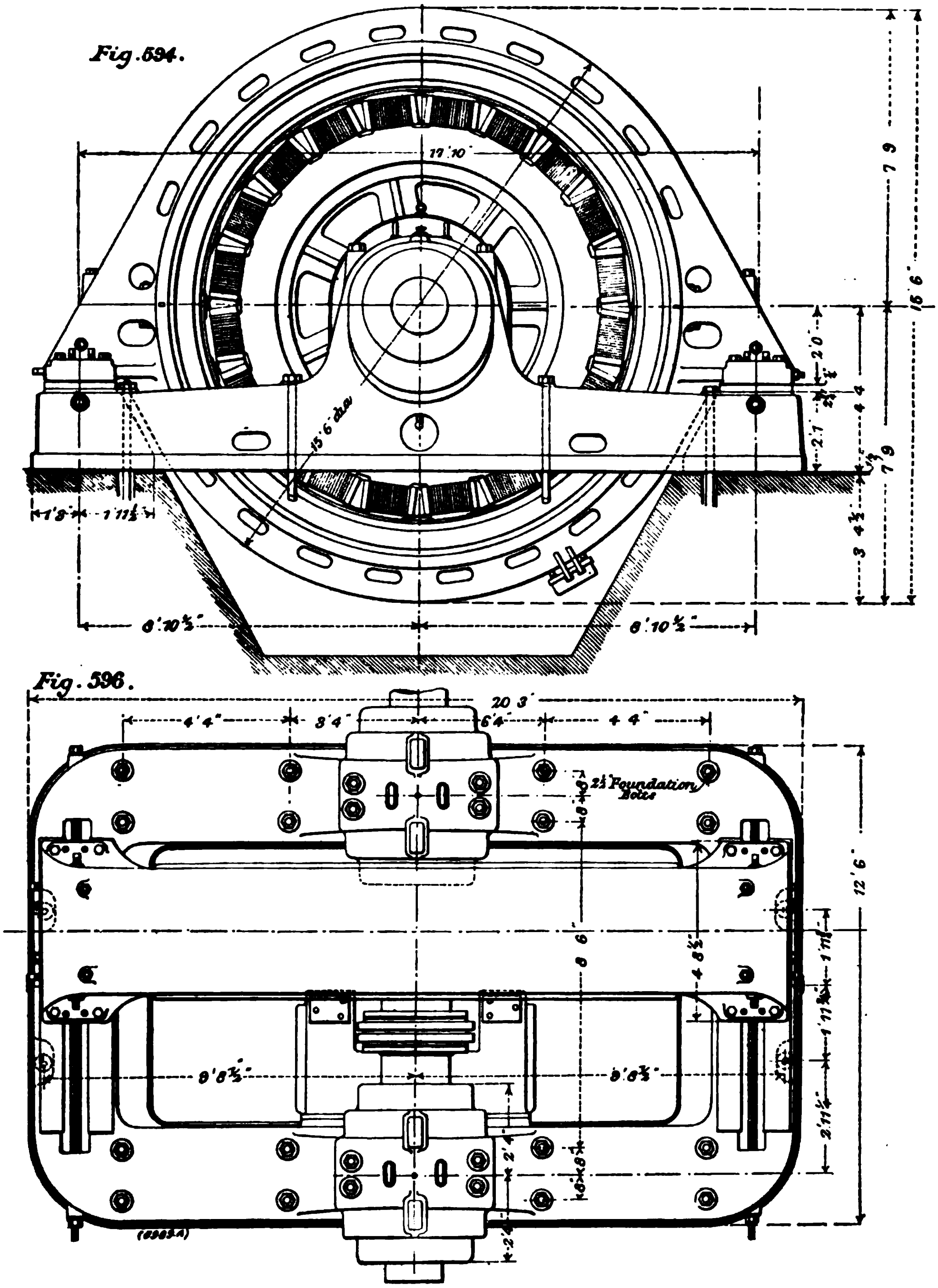


Fig. 596.

FIGS. 594 AND 596. 3750-KILOWATT WESTINGHOUSE QUARTER-PHASE GENERATOR

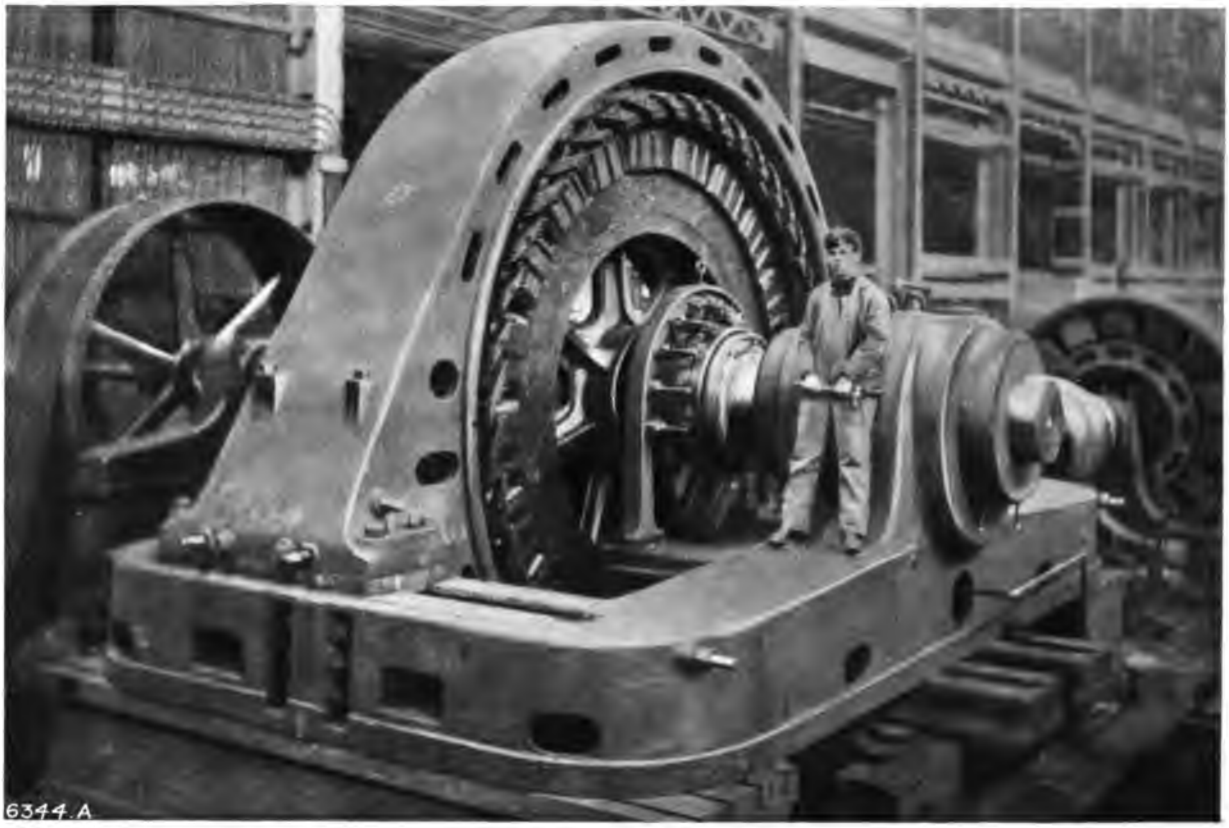


FIG. 590. 3750-KILOWATT, 20-POLE, 30 CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

FIG. 591. UPPER HALF OF ARMATURE OF THE WESTINGHOUSE GENERATOR

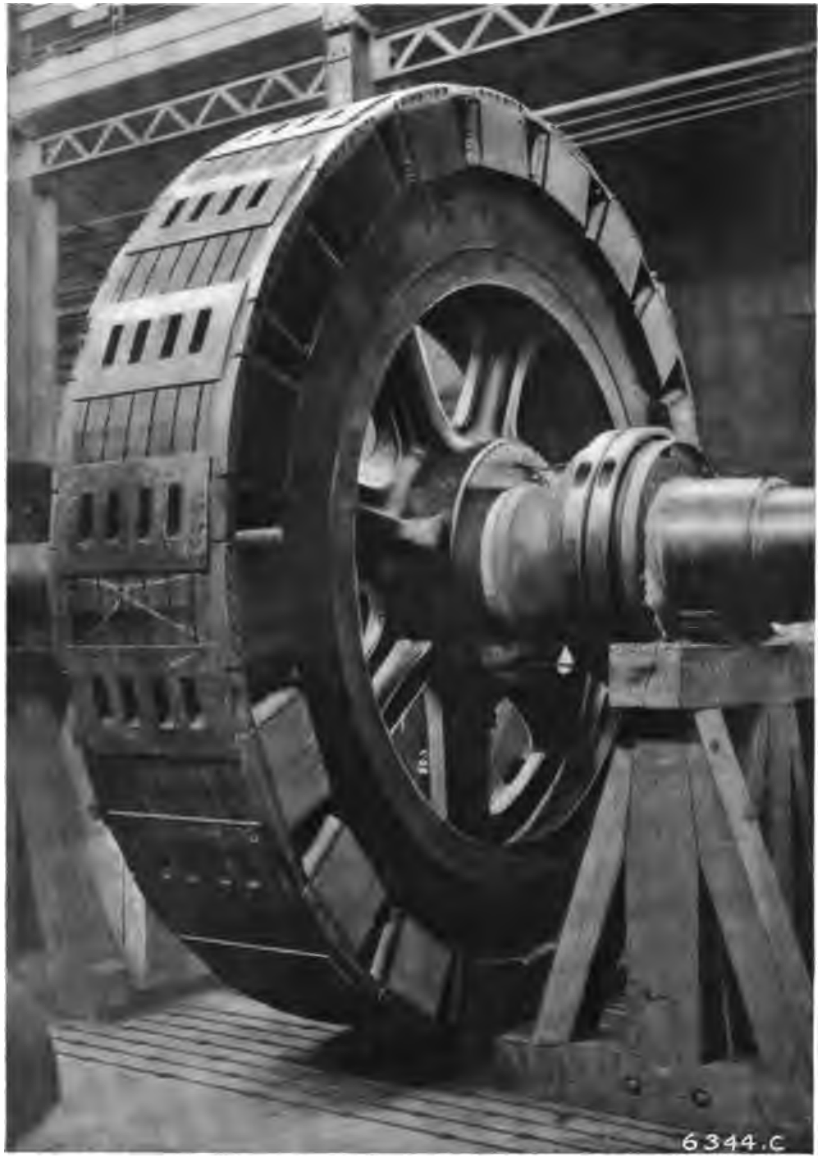


FIG. 592. ROTATING FIELD OF THE WESTINGHOUSE GENERATOR

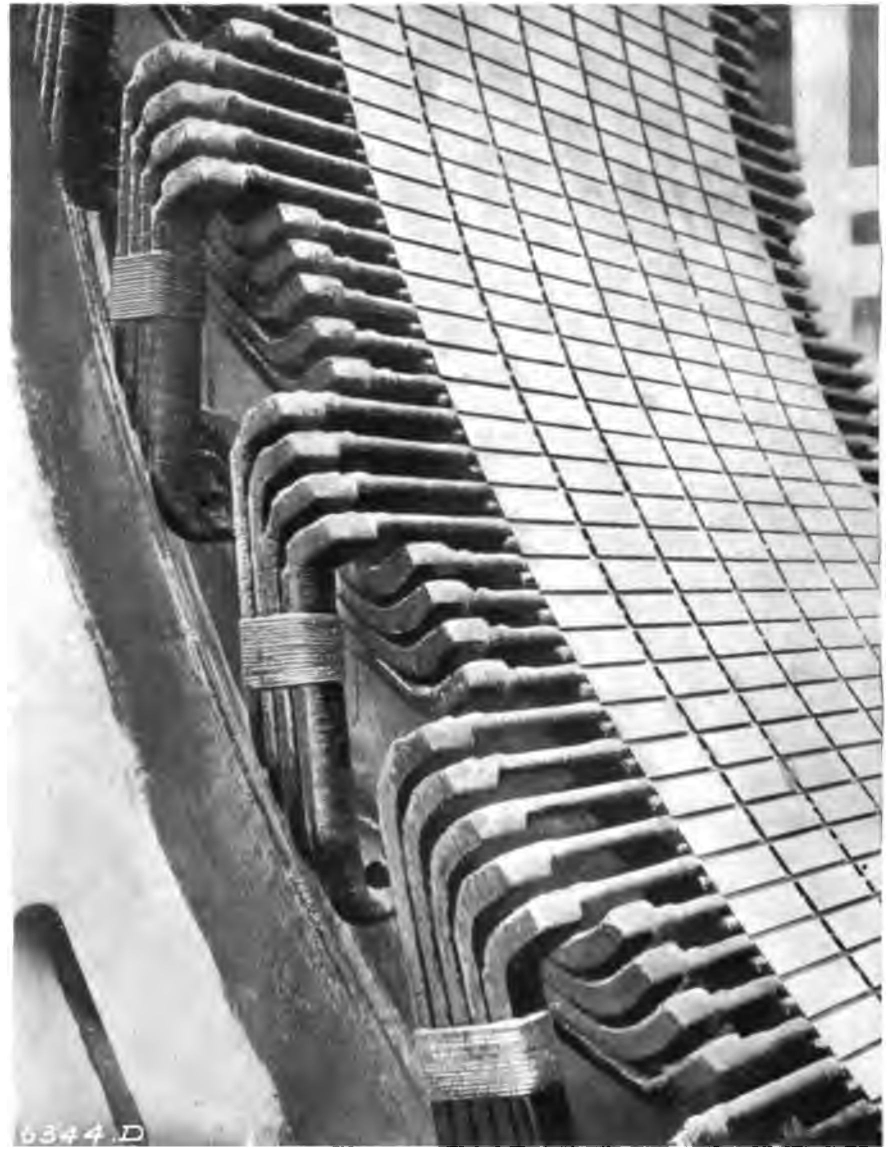


FIG. 593. PORTION OF ARMATURE CORE AND WINDING OF THE WESTINGHOUSE GENERATOR

of the armature core and winding. Drawings of the machine are given in Figs. 594 to 610 (see pages 511 to 518). Table LXXXVI. contains its leading dimensions.

TABLE LXXXVI.—3750-KILOWATT QUARTER-PHASE GENERATOR

Rated output	3750 kilowatts
Number of phases	2
Periodicity in cycles per second	30
Speed in revolutions per minute	180
Voltage per phase	2200
Number of poles	20

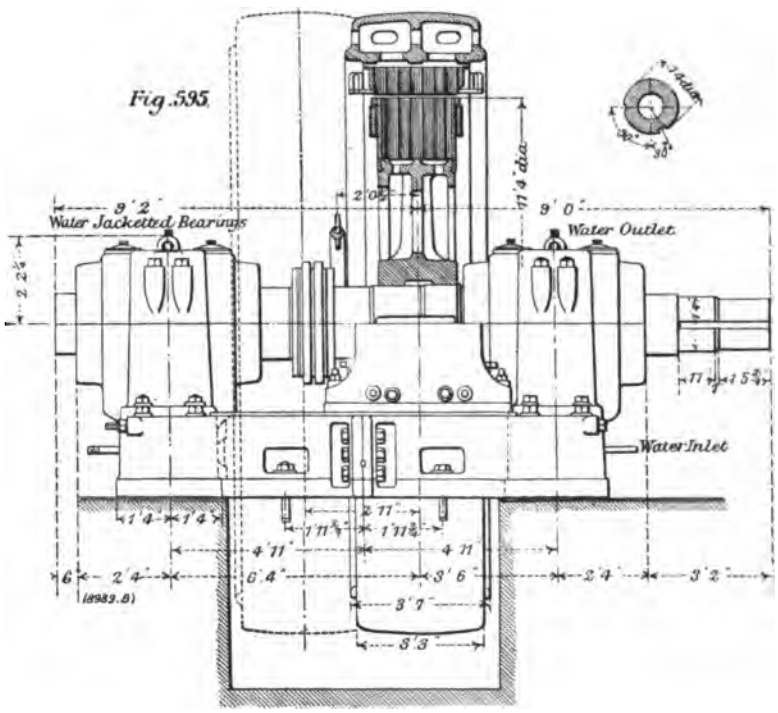


FIG. 595. 3750-KILOWATT WESTINGHOUSE QUARTER-PHASE GENERATOR

Data for Armature Iron:

External diameter of armature laminations	154 in.
Diameter at the bottom of the slots	$140\frac{15}{16}$ in.
Internal diameter of armature laminations (*i.e.*, at air gap) ...	$137\frac{1}{2}$ „
Gross length of core between flanges	25 „
Number of ventilating ducts	6
Width of each ventilating duct	$\frac{3}{8}$ in.
Per cent. insulation on core plates	10 per cent.
Effective length of armature core	$20\frac{1}{2}$ in.
Number of slots...	360
„ per pole per phase	9
Width slot + tooth at bottom of slot	1.23 in.
„ „ armature face	1.2 „

Depth of slot	$1\frac{23}{32}$ in.
Width „	$\frac{15}{32}$ „
Width of slot opening	$\frac{3}{16}$ „
Thickness of the tip at the slot opening	$\frac{3}{32}$ „
Width of tooth at root	0.76 „
„ narrowest point	0.73 „
„ gap	1.01 „

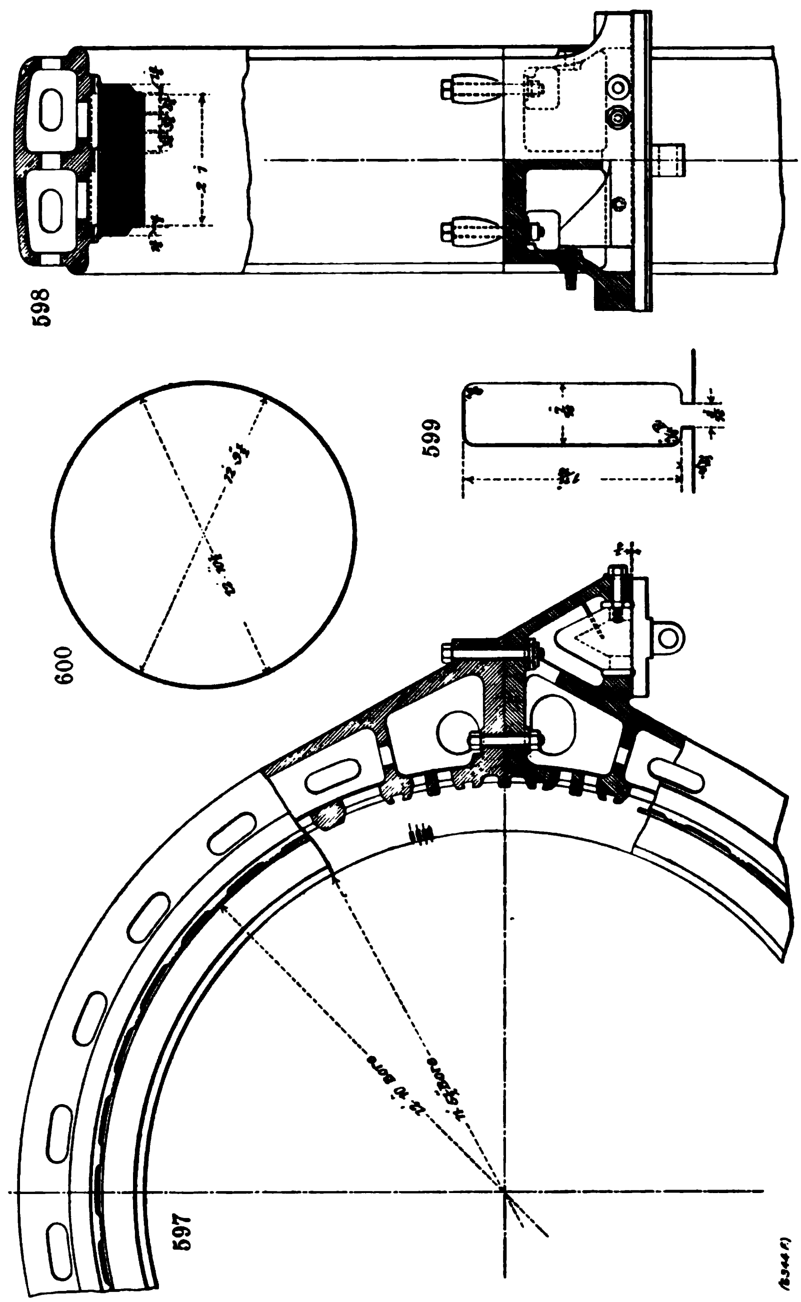
Data for Rotating Iron:

Radial depth of air gap at the middle of the pole arc	$\frac{3}{4}$ in.
Average radial depth	$\frac{13}{16}$ „
Pole-face diameter	136 „
Diameter at bottom of magnet core	$113\frac{7}{8}$ „
Total radial length „	$11\frac{1}{16}$ „
Material of magnet core	Laminated steel
„ yoke	„
Polar pitch at air gap	21.3 in.
Length of pole arc	14 „
Ratio of pole arc to pole pitch	65.7 per cent.
Length of magnet core lamination	$23\frac{1}{2}$ in.
Number of ventilating ducts	6
Width of ventilating duct	$\frac{3}{8}$ in.
Cross-section of magnet core	280 square inches

The field is punched in ten segments, each covering one full pole and two adjacent half-poles. The sheet steel is built up overlapping.

Data of Armature Copper:

Number of conductors per slot	1
„ slots	360
„ conductors	360
„ turns	180
„ phases	2
(The winding is arranged for two independent circuits.)	
Number of turns per phase	90
„ coils „	20
„ „ per pole per phase	1
Size of conductor (in slot)	$\frac{1}{4}$ in. × $1\frac{1}{2}$ in.
„ (end connection)	$\frac{3}{8}$ in. × $1\frac{1}{2}$ in.
Cross-section of conductor in slot	0.375 sq. in.
„ end connection	0.56 „
Length of two-face conductors	80 in.
„ two-end connections	$37\frac{3}{4}$ „
Mean length of one turn ($80 + 37\frac{3}{4}$)	$117\frac{3}{4}$ „
Resistance of armature winding per phase at 60 deg. Cent. (calculated)	0.0196
Resistance of armature winding per phase at 22 deg. Cent. (observed) for phase 1-3	0.01740
Ditto for phase 2-4	0.01745



FIGS. 597 TO 600. DETAILS OF 3750-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

Data of Magnet Copper:

Number of turns per spool (wound on edge)	60
Size of conductor	$\frac{1}{8}$ in. × $1\frac{5}{8}$ in.
Number of spools in series	20
Total resistance at 20 deg. Cent. (observed)	0.3307

Characteristic Data

The flux per pole M at no-load is 20 megalines, which corresponds to the following densities at no-load :—

	C.G.S. Lines per Square Centimetre.
Density in armature core	11,500
,, teeth...	16,500
,, pole-face	8,900
,, magnet core (leakage factor = 1.3)	14,400
,, yoke	13,300

The full-load current per phase is $\frac{3750}{2 \times 2200} = 850$ amperes, and the corresponding current density in the armature conductor is 2280 amperes per square inch for conductor in slot, and 1500 amperes per square inch for end connection.

Armature Demagnetisation:

Turns per phase	90
,, pole per phase	4.5
Current in conductor	850 amperes
Armature ampere turns per pole per phase	3820

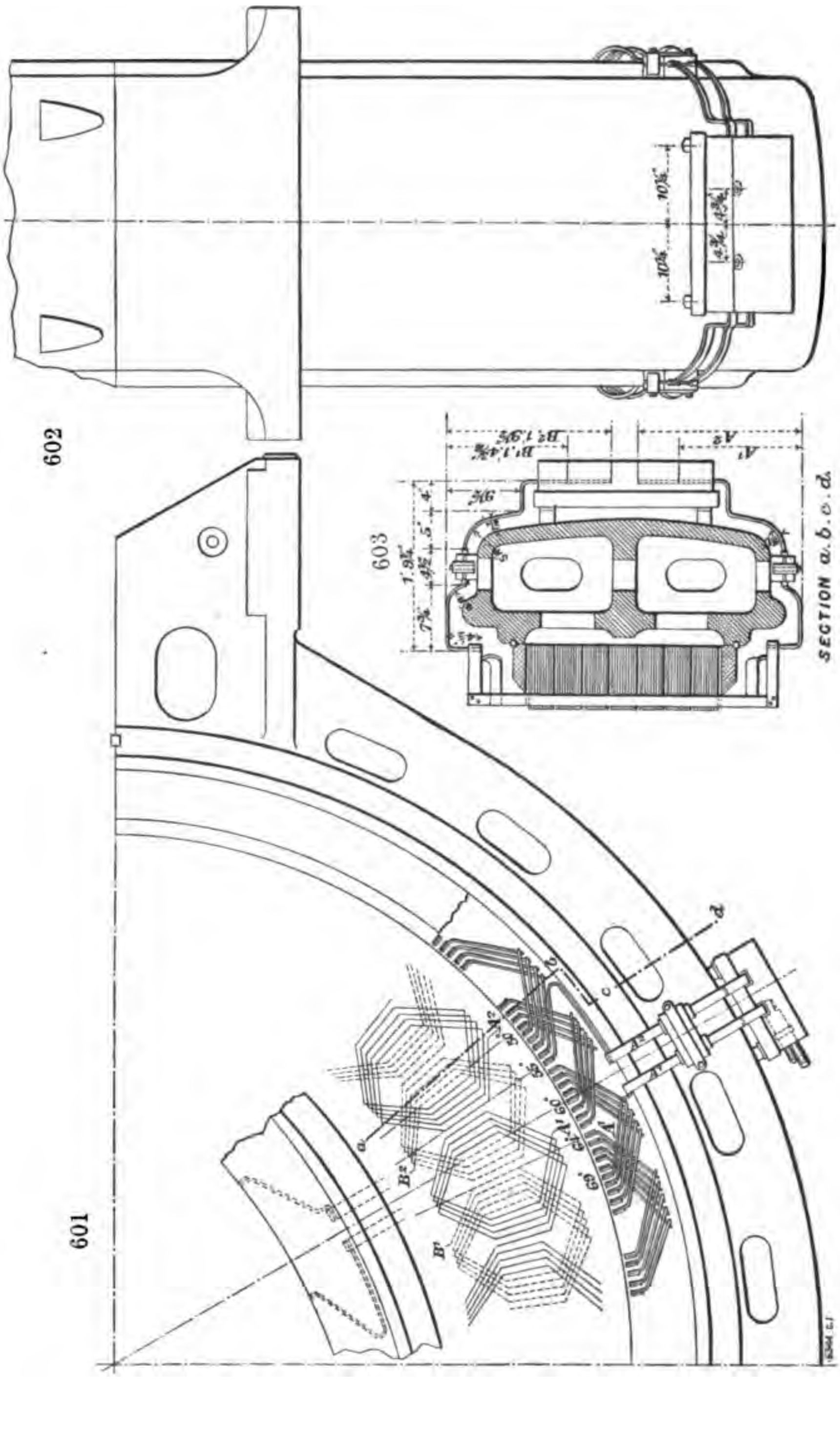
The demagnetising ampere turns of a two-phase winding are $\sqrt{2}$ times the maximum ampere turns of one phase, therefore demagnetising ampere turns per pole ... $3820 \times \sqrt{2} \times \sqrt{2} = 7640$

The field ampere turns necessary to produce the full-load current at short circuit were observed to be 5800. This is 30 per cent. lower than the above value; the difference is to be explained by the large percentage which the width of a coil constitutes of the pole-pitch (50 per cent.), and by the deep air-gap employed.

Let us take for the calculation of the armature reaction the observed value, 5800.

A suitable value for the lines per ampere turn per inch gross length would be 20.

It has been shown that the Glasgow generator had 24.6 lines per ampere turn per inch gross length of armature, and the Central London Railway generator 33.5 lines. In the present alternator the inductance



FIGS 601 TO 603. DETAILS OF 3750-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

expressed in lines per inch gross length would be smaller, because (1) the coil is spread out more than in the previous cases, (2) because the air-gap of this machine is exceedingly large ($\frac{13}{16}$ in.), and (3) because two coils per pair of poles per phase are employed, thereby reducing the inductance of the end connections, which constitute a great part of the total inductance. (See paper entitled "A Contribution to the Theory of the Regulation of Alternators," read before the American Institute of Electrical Engineers, April 22nd, 1904.) The value chosen corresponds well with the values

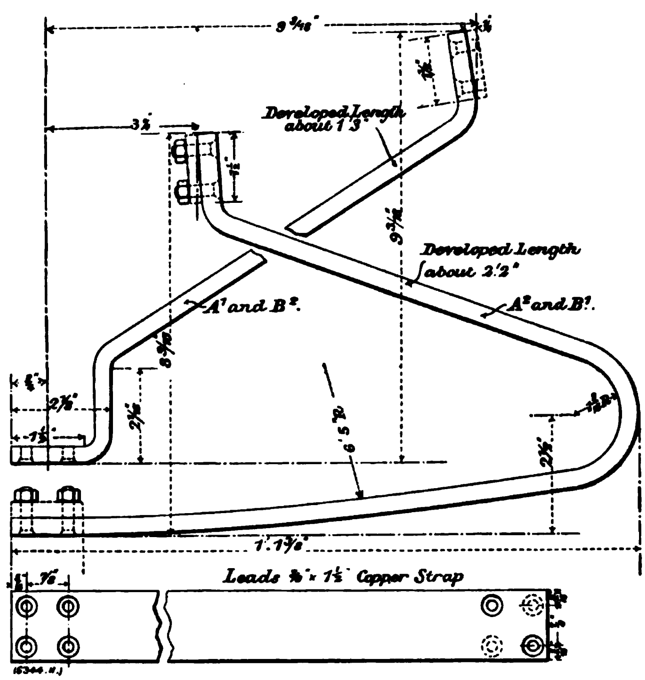


FIG. 604. DETAILS OF TERMINAL CONNECTIONS

given in this paper for partly-closed slots and well-distributed windings. Observed data of the actual inductance was not available.

The calculation of the reactance of the armature winding has been worked out as follows :—

Lines per ampere turn per inch gross length of armature ...	20
Gross length of armature	25 in.
Lines per ampere turn = 25 × 20...	500
Number of coils per phase	10
„ turns per coil	9
Inductance of one coil ($500 \times (9)^2 10^{-8}$)	0.000405 henry
„ per phase (10×0.000405)	0.00405 „

Reactance ($2\pi \times 30 \times 0.00405$)	**0.76 ohm**
„ voltage at full load (850×0.76)...	**645 volts**
Terminal voltage per phase	**2,200 „**
Tan ϕ at unity power factor $\left(\frac{645}{2200}\right)$	**0.294**
Sin ϕ at unity power factor	**0.282**
Armature demagnetisation (5800×0.282)	**1,630**
Field ampere turns at no-load (observed)	**13,500**

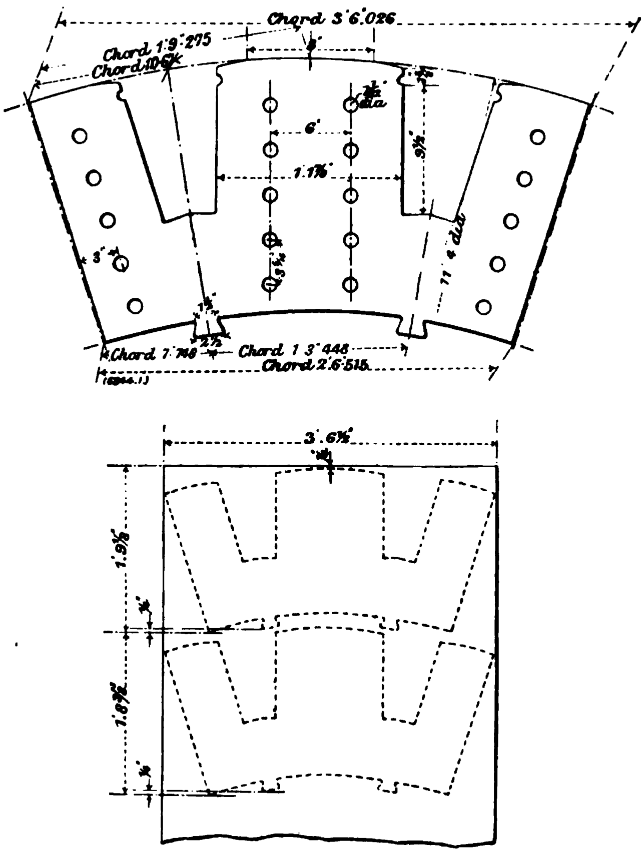
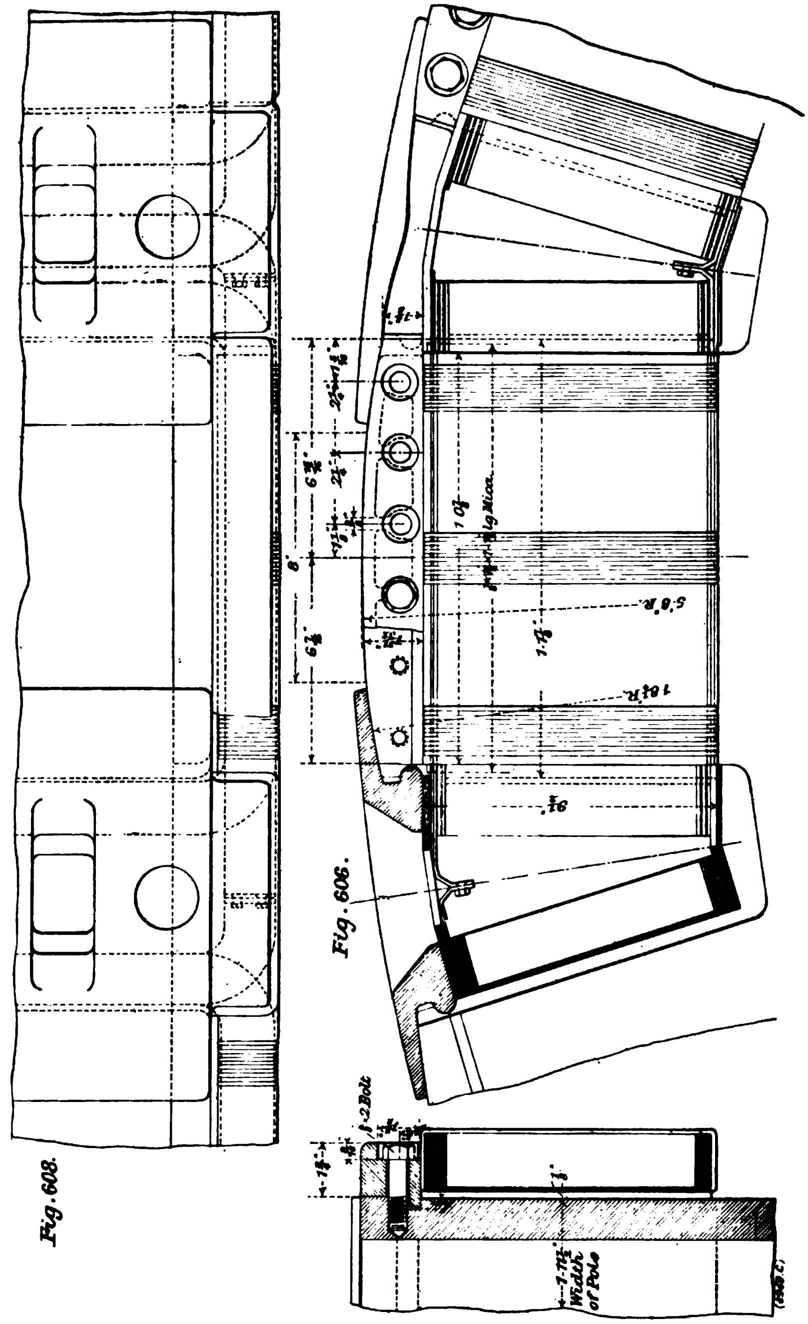


FIG. 605. FIELD MAGNET STAMPINGS

Drop through ohmic resistance (16 volts)	**0.74 per cent.**
Field ampere turns for saturation at full load	**13,650**
Armature demagnetising ampere turns	**1,630**
Total ampere turns per field spool	**15,280**

The same calculation has been repeated for other voltages, and the results have been plotted in Figs. 611 to 613, pages 519 and 520, in curves showing the influence of various power-factors, and of lagging and leading currents. All curves have been calculated, as shown in the earlier part of this Chapter.



FIGS. 606 AND 608. DETAILS OF 3750-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

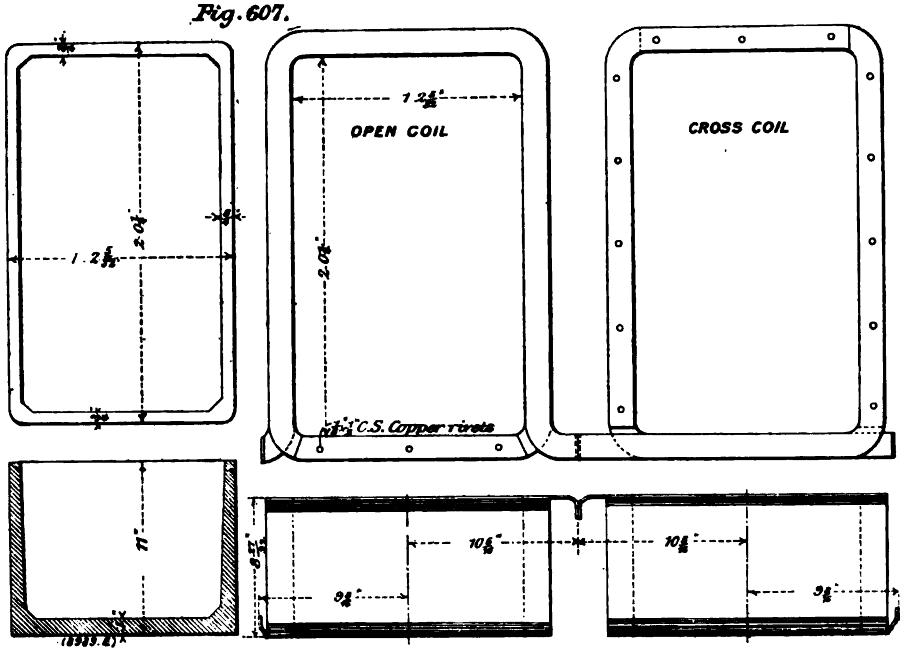


FIG. 607. DETAILS OF 3700-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

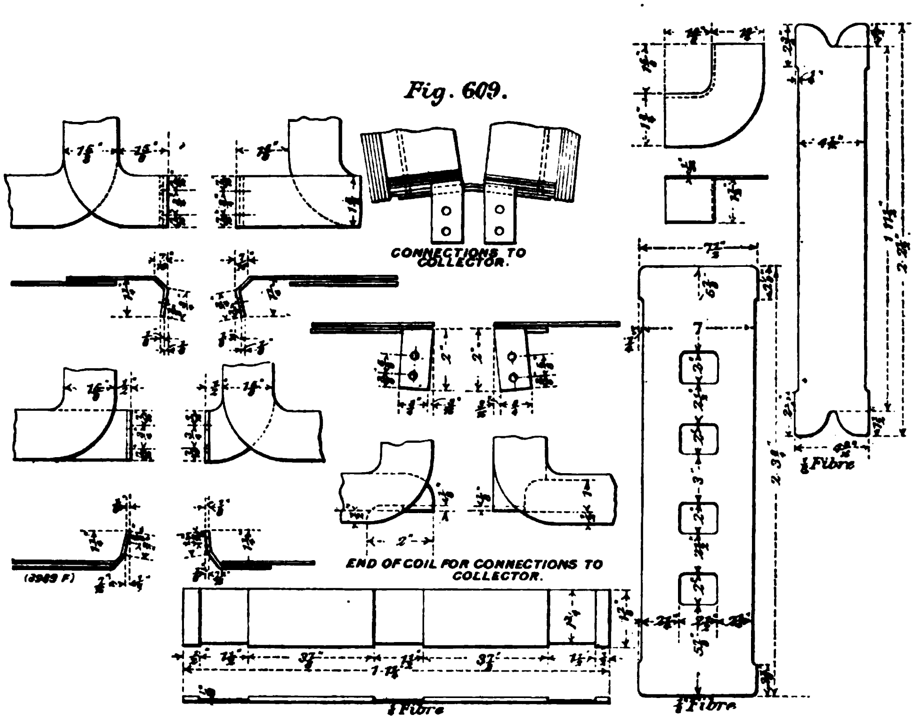


FIG. 609. DETAILS OF 3700-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

Losses:

1. Armature C^2R loss:	
Amperes per phase	850
Resistance at 60 deg. Cent.	0.0196
C^2R loss per phase	14,100
Total C^2R loss of armature	28,200 watts
2. Armature iron loss (observed)	45,000 „
Total armature loss	73,200 „

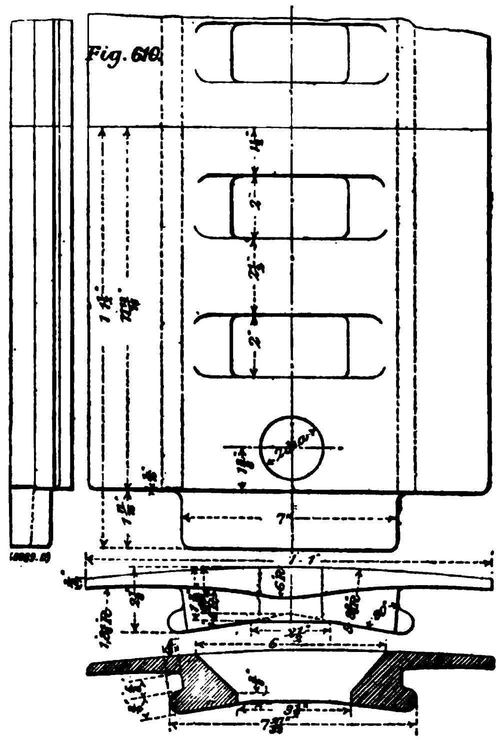


FIG. 610. DETAILS OF 3700-KILOWATT, 20-POLE, 30-CYCLE, 2200-VOLT WESTINGHOUSE GENERATOR

3. C^2R loss in field winding at full load and cos φ = 1	
Ampere turns at full load	15,820
Amperes at full load	255
Resistance of field winding at 60 deg. Cent.	0.37 ohm
C^2R loss in field winding	24,000 watts
Bearing friction and windage (average of two machines tested) ...	19,000 „
Total loss at full load and cos ϕ = 1	116,200 „
Efficiency at „ „	0.970

HEATING

The generator was tested with 0 ampere and 2500 volts for twelve hours, and showed after that time the following thermometrically determined temperature increase above the surrounding air:—

	Deg. Cent.
Armature iron	29.5
,, copper	22.5
Magnet core	13.5
Field spool	32.5
Collector	23.5

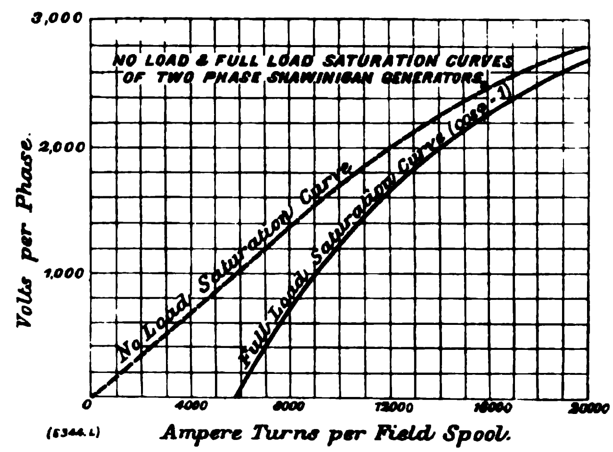


FIG. 611. NO-LOAD AND FULL-LOAD SATURATION CURVES

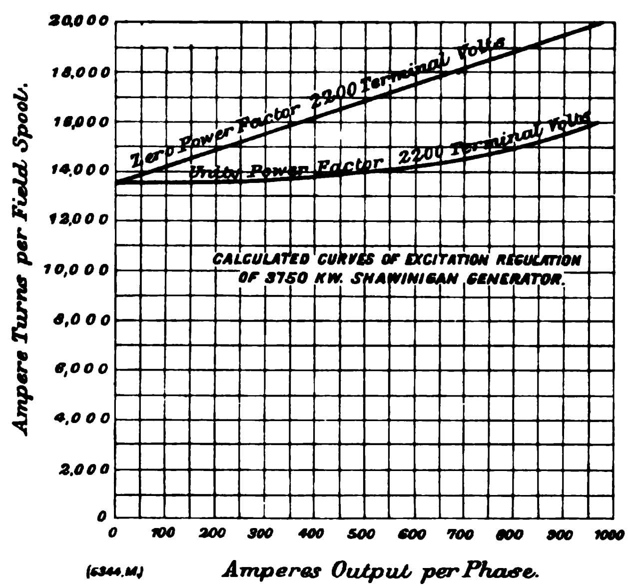


FIG. 612. EXCITATION REGULATION CURVES

The armature loss during this test was 54 kilowatts, and, making the approximate assumption of proportionality between losses and temperature rise, the temperature rise at full-load will be $\frac{73,200}{54,000} = 1.35$ times higher

than the mean temperature of armature copper and iron observed during the no-load test, that is—$1.35 \times \frac{29.5 + 22.5}{2} = 35$ deg. Cent.

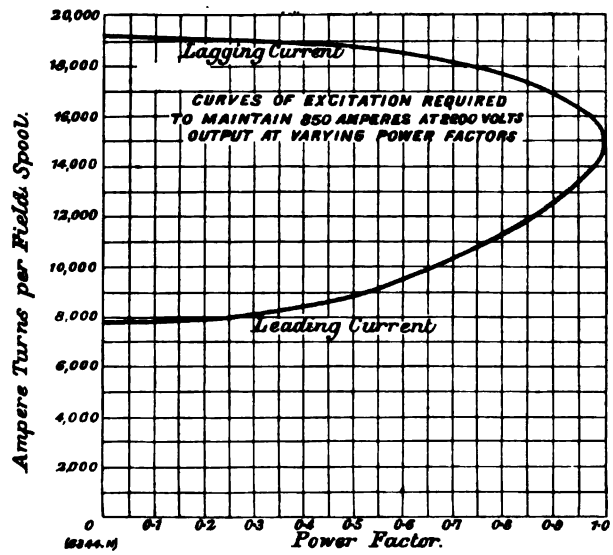


FIG. 613. EXCITATION CURVE

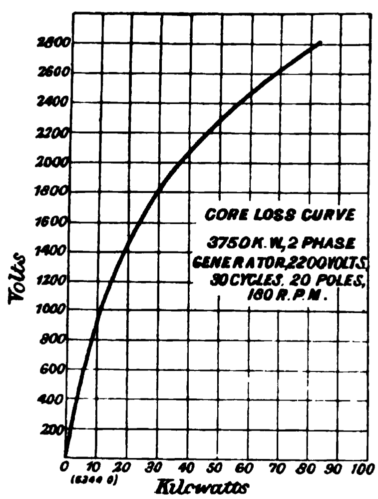


FIG. 614. CORE-LOSS CURVE

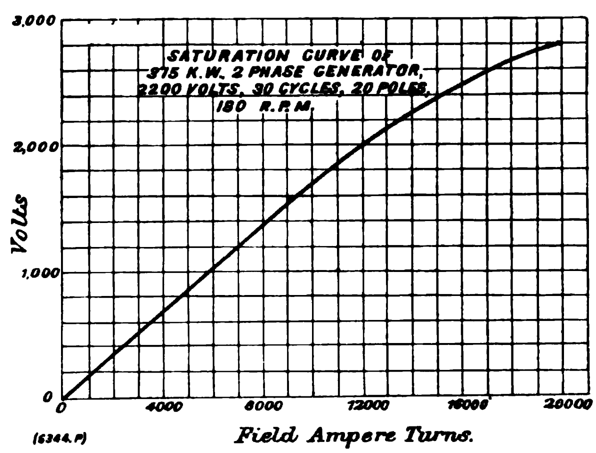


FIG. 615. NO-LOAD SATURATION CURVE

The field loss during the test was 28,000 watts; the temperature rise of the field spools would, therefore, at full-load be 28 deg. Cent. above the surrounding air.

In Fig. 614 is given a core-loss curve for one of the machines tested,

and in Fig. 615 is given its no-load saturation curve. The amperes per phase on short-circuit are shown in Fig. 616.

The weights of the machine are as follows:—

Stationary Part:

	Lb.
Bed-plate	73,340
Upper half of armature and yoke	34,420
Lower „ „ „	37,720
Details	6,320
Total weight of stationary part	151,800

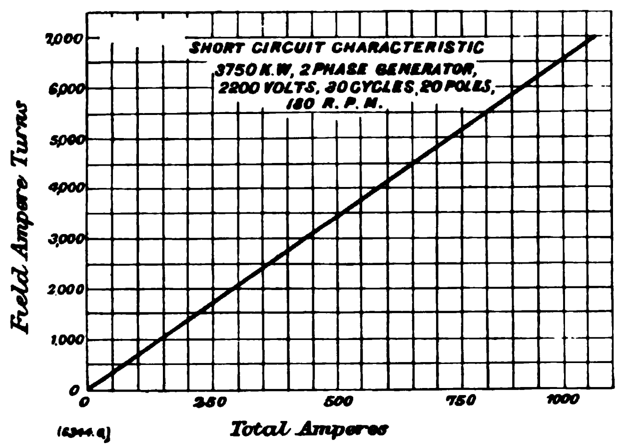


FIG. 616. SHORT-CIRCUIT CURVE

Rotating Part:

Coils	6,600
Coil supports	2,480
Spider and field core	47,800
Shaft	14,980
Details	2,420
One-half coupling	5,390
Total weight of rotating part	79,670
„ machine (including one-half coupling)	231,470

Two of these machines were built, and the test curves are for the second machine. The first machine showed very closely the same characteristics throughout, the windage and friction being about 2 kilowatts lower, and the iron loss about 2 kilowatts higher than on the second machine.

Description of a Three-Phase, 850-Kilowatt, 5000-Volt, 25-Cycle, 32-Pole Alternator

This machine is one of six supplied by the British Thomson-Houston Company for the Central London Railway, and installed in the Shepherd's Bush power-house in 1898. The generators are direct-coupled to horizontal, cross-compound, Corliss type engines, built by the E. P. Allis Company, of Milwaukee. The engines run at 94 revolutions per minute at full-load, and are provided with a 50-ton flywheel of 18 ft. outside diameter, the weight of the rim being 30 tons.

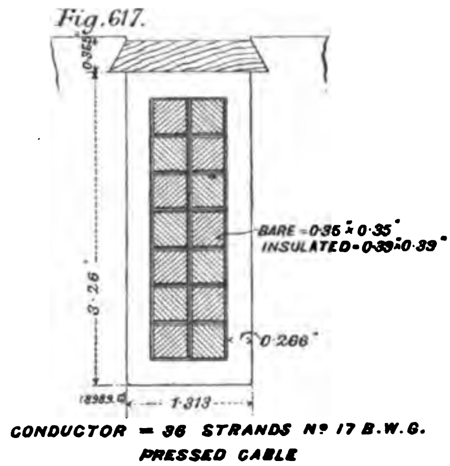


Fig. 617. Section Through Slot

The alternators are of the internal revolving field type, the field having 32 laminated pole-pieces, bolted on to a cast-steel ring carried on a cast-iron spider pressed on the engine crankshaft.

The armature core is built up of wrought-iron laminations 0.014 in. thick, secured by dovetails and clamps to a cast-iron frame. The armature slots are 192 in number, corresponding to two per pole per phase. They are open at the core face to admit of former wound coils being used, which latter are secured by wooden wedges held in dovetail grooves at the head of the slots. Fig. 617 shows a section through the slot.

The armature conductor consists of 36 strands of No. 17 B.W.G. pressed cable, whose outside dimensions are 0.35 in. by 0.35 in. The current density at full-load current is 1040 amperes per square inch.

There are 16 coils in series per phase, of 28 turns each coil, making 896 active conductors per phase, or 2688 conductors for the three phases,

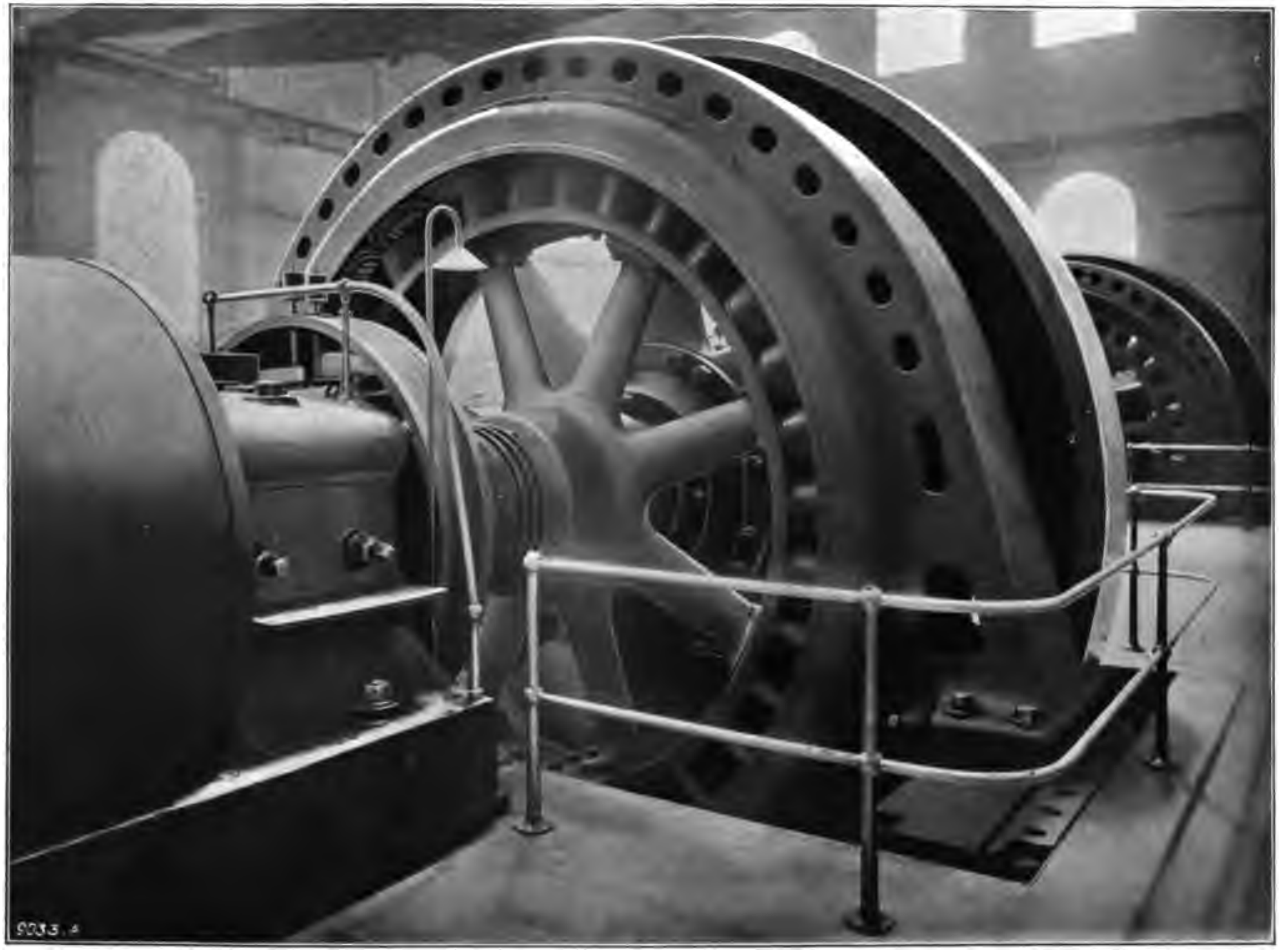


FIG. 618. THREE-PHASE, 850-KILOWATT, 5000-VOLT, 25-CYCLE, 32-POLE ALTERNATORS FOR THE CENTRAL LONDON RAILWAY

the three phases being star-connected, and the neutral point earthed. The coils are arranged in two layers at the ends, so that any one coil can be removed without disturbing any of the others; for this purpose and for inspection the complete armature is capable of being removed bodily sideways, clear of the magnet wheel.

The field winding consists of copper strip wound on edge, of section 1.5 by 0.08 in. There are 79½ turns on each pole, the coils being wound on formers slipped on to the cores and held in place by wooden flanges. By adding the half-turn, the terminals are brought out to opposite sides of the wheel, so that by joining adjacent terminals a simple and efficient system of coupling is obtained. The field current at full-load and unity power-factor is 109 amperes, giving a current density of 920 amperes per square inch. The exciter voltage is 125, and the current is conveyed to the field by two rings, each having two copper brushes. The magnet wheel complete weighs 34,000 lb.; and the complete armature 48,600 lb.

Fig. 618, Plate IX., is a view of these machines.

Fig. 619 is an outline drawing giving the leading dimensions of one of them.

Table LXXXVII. is a general specification for the machine, in which has also been incorporated a very comprehensive amount of data from the test results on one of the alternators.

TABLE LXXXVII.—SPECIFICATION FOR 3-PHASE, 850-KILOWATT ALTERNATOR

Rated output at unity power factor...	850 kilowatts
Number of phases	3
Periodicity in cycles per second	25
Speed in revolutions per minute	94
Number of poles...	32
Terminal voltage	5000
Current per terminal at full load	98
Connection of armature	Y
Voltage per phase	2880
Data for Armature Iron:	
External diameter of laminations	162 in.
Internal " "	144 "
Diameter at bottom of slots	151¼ "
Gross length of core between flanges	14½ "
Number of ventilating ducts	5
Width of each duct	½ in.
Effective length of armature core (iron)	10¾ "
Ratio of effective length to gross length	0.745
Per cent. insulation on core plates	10 per cent.

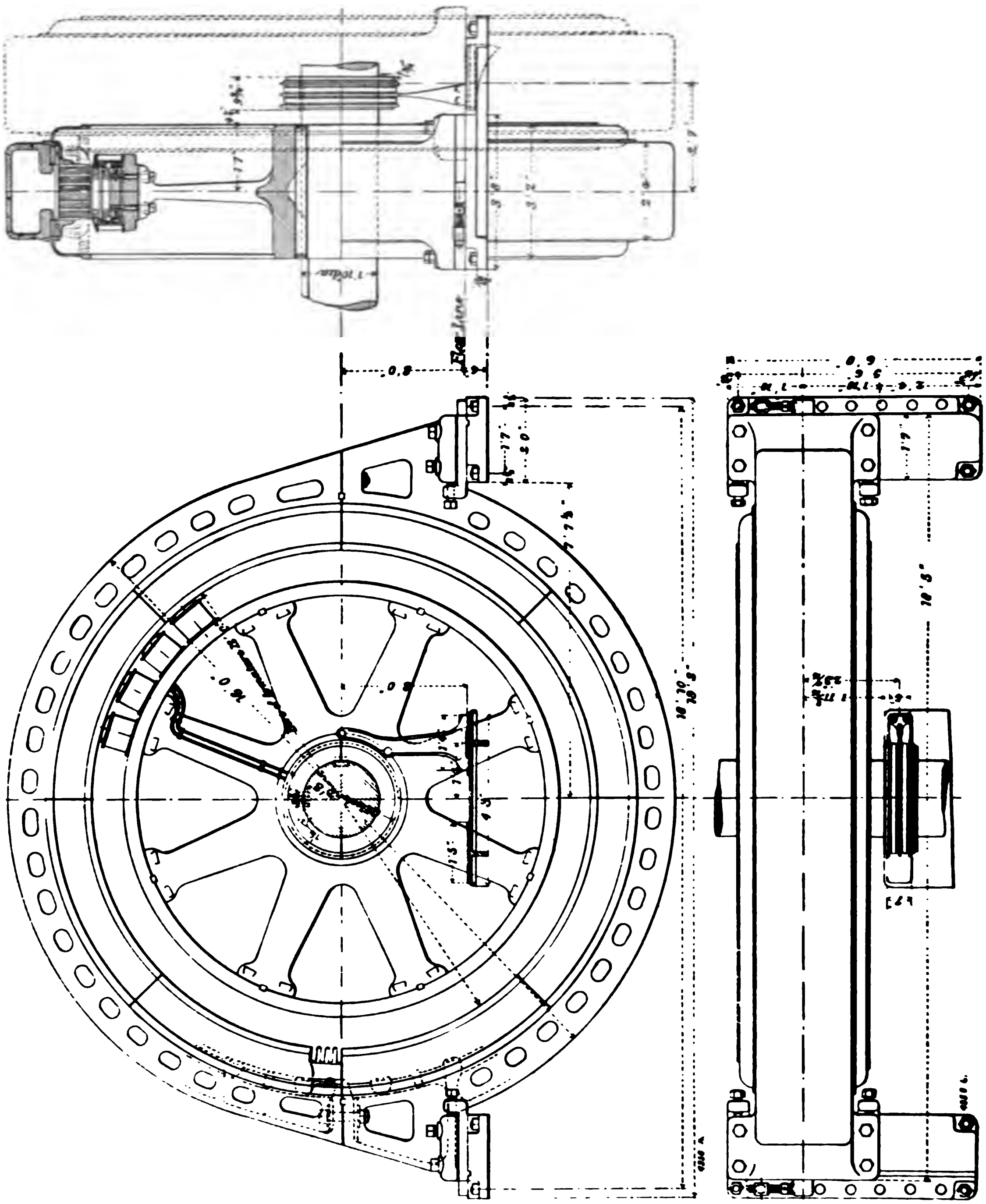


FIG. 619. CENTRAL LONDON RAILWAY 850-KILOWATT 3-PHASE GENERATOR

Thickness of laminations	0.014 in.
Number of slots	192
„ per pole per phase	2
Depth of slot	$3\frac{5}{8}$ in.
„ above winding space	0.53 „
Width of slot	1.313 „
Pitch of slots at armature face	2.36 „
Ratio of slot width to pitch	0.557
Width of tooth at armature face	1.047 in.
Ratio of tooth width to pitch	0.443
Pitch of slots at bottom of slot	2.48 in.
Width of tooth at root	1.167 in.

Data for Rotating Field Magnets:

Number of poles	32
Diameter over field poles	$143\frac{3}{8}$ in.
Radial length of air gap (minimum)	0.3125 „
„ „ (effective)	0.391 „
Polar pitch at air gap	14.1 „
Circumferential length of pole arc	9 „
Ratio of pole arc to pole pitch	64.3 per cent.
Length of pole-piece parallel to shaft	$14\frac{1}{2}$ in.
Radial length of pole-piece	8.75 „
Breadth of pole across shaft	6.5 „
Peripheral speed per second at pole-face	59 ft. per second

Data for Armature Copper:

Number of conductors per slot	14
Total number of conductors	2688
Number of conductors per phase	896
„ turns „	448
„ coils „	16
„ turns per coil	28
„ slots per pole per phase	2
Each conductor consists of 36 strands of No. 17 B.W.G.	
Effective cross-section	0.095 sq. in.
Current density	1040 amperes per square inch
Arrangement of conductors in slot	7 × 2
Dimensions of conductor bare (pressed cable)	0.35 × 0.35 in.
„ „ insulated	0.39 × 0.39 „
Thickness of insulation in slot	0.266 in.
"Free" length per turn	71.5 „
"Effective" length per turn	21.5 „
Mean length of one turn	93 „
Resistance per phase at 20 deg. Cent.	0.294 ohms
„ „ 55 „	0.332 „
Space factor in slot	0.275

Data for Field Copper:

Number of turns per spool	$79\frac{1}{2}$
Size of conductor	1.5 in. × 0.08 in.
Internal periphery of winding	15 ,, × 7 ,,
External ,, ,,	18 ,, × 10 ,,
Depth of winding	1.5 in.
Axial length between bobbin flanges	7.25 ,,
Thickness of insulation between turns	0.011 in.
Total cross-section of copper on bobbin	9.5 sq. in.
Length of mean turn	50 in.
Weight of copper per spool	153 lb.
Number of spools	32
Total weight of copper in 32 spools	4900 lb.
Resistance per spool at 20 deg. Cent.	0.0226 ohms
,, of 32 spools in series	0.722 ,,
Exciter voltage	125

Excitation for Full Load at Unity-Power Factor:

Ampere turns per pole	8650
Current in field	109 amperes
Current density in field copper	920 amperes per square inch
Watts lost in excitation (total)	8600
,, per spool	269
External surface of winding	406
Watts per square inch of surface	0.66

Magnetic Data:

Flux in armature per pole at full load	5.82 megalines
Corresponding densities:	C.G.S. Lines per Sq. In.
Armature core	50,200
Teeth	102,500
Pole-face	46,200
Magnet core (leakage factor = 1.27)	86,000
Yoke	51,400
Leakage factor:	
Calculated at no-load	1.2
,, full-load	1.27

Weights:

	Lb.
Magnet cores	6,800
,, yoke	7,800
Armature laminations	10,300
Effective iron (total)	24,900
Armature copper	3,800
Field ,,	4,900
Effective ,, (total)	8,700
Total weight of effective material	33,600
Weight of effective material in pounds per kilowatt output	40
,, magnet wheel complete	34,000
,, armature ,,	48,600

Data from Tests:

Field-ampere turns for 5000 volts, no-load	7650
„ „ „ full-load	8650
„ „ at full inductive load (90 deg.)	11250
Voltage on field, no load	77.1
„ „ full non-inductive load	87.3
„ „ full inductive load...	113.5

Regulation:

Inherent regulation at full non-inductive load excitation ...	5 per cent.
Excitation regulation	13 „
Amperes on short circuit at full non-inductive load excitation ...	228
Ratio to full-load current	2.32

Losses:

	Watts.
Core loss:	
Iron loss at 5000 volts no-load	19,000
„ full-load	19,380
Full load, C^2R armature	9,600
„ excitation watts	9,500
„ total losses...	38,480
No-load, „	26,520

Efficiency:

Calculated for 5000 volts no load and 5000 volts full load.

	Including Field Losses. Per Cent.	Excluding Field Losses. Per Cent.
1¼ load	96.0	96.8
Full „	95.7	96.6
¾ „	95.0	96.2
½ „	93.4	95.0
¼ „	88.5	91.3

Heating:

Rise in temperature after 11½ hours' run at 5200 volts and 125 amperes (= 1120 kilowatts).

	Deg. Cent.
Armature core surface	23
„ „ ventilating ducts	22.3
„ conductors, top coil	18.8
„ „ side coil	27
„ „ by rise in resistance	35
Collector rings	20
Pole-tip, leading...	11.5
„ trailing...	12
Separately-excited field (at 109 amperes)	25.7
Frame	9

Heating Constants:

Radiating surface, armature, for core loss only	... ...	6,580 sq. in.
„ „ field	... ...	13,000 „
Watts per square inch of armature radiating surface	... ...	2.95
„ „ field „ „	... ...	0.66
Deg. Cent. rise per watt per square inch, armature	... ...	78
„ „ „ field	... ...	39

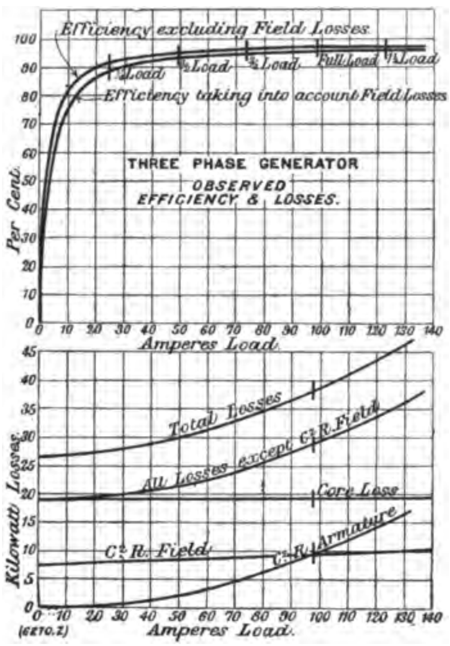


Fig. 620. Efficiency and Loss Curves

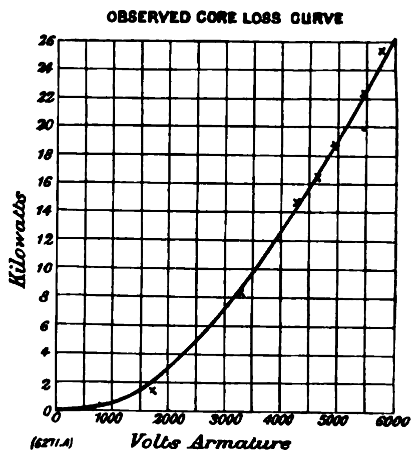


Fig. 621. Loss Curve

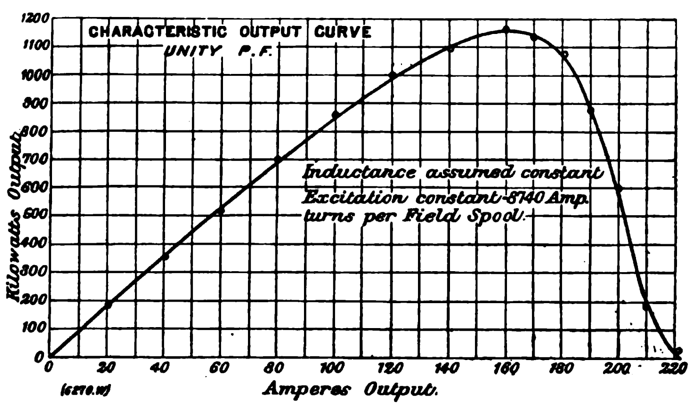


Fig. 622. Output Curve at Unity Power Factor

Resistances:

		Cold.	Warm.
Armature between rings ..	...	0.588 (20 deg. Cent.)	0.664 (55 deg. Cent.)
Field	...	0.722 (20 deg. Cent.)	0.802 (50 deg. Cent.)

Fig. 620 shows the observed curves for losses and efficiency ; including and excluding excitation losses.

In Fig. 621 is given a curve for the observed core loss at various voltages, corresponding to various flux density values in the armature.

Fig. 622 is a characteristic output curve connecting amperes output and kilowatts output at unity power factor for a constant field excitation of 8740 ampere turns per field spool.

A number of other characteristic curves for this machine have already been given in Figs. 488 and 489, page 451 ; Fig. 491, page 453 ; Figs. 494 and 495, page 456 ; and Figs. 502 to 504, pages 460 and 461 ; the subject of armature reactions and regulation, and the calculation of these curves having also been dealt with at some length.

Output Coefficient

It has been alleged—and to a certain extent rightly—that the rated output of a machine is proportional to (gap diameter)^2 × gross length of armature × revolutions per minute, and the ratio

$$\frac{\text{Output in watts}}{(\text{Gap diameter in cms.})^2 \times (\text{gross length of armature in cms.}) \times \text{R.P.M.}}$$

has been designated the "output coefficient." As a matter of interest, this output coefficient has been calculated for the three large alternators described in this Chapter, and has been arranged in Table LXXXVIII. :—

Table LXXXVIII.

Type of Alternator.	Output in Watts.	Speed.	Periodicity.	Gap Diameter in Cms.	Gross Length of Armature Core in Cms.	$\frac{D^2L}{10^6}$	Output Co-efficient.
Central London Railway ...	850,000	94	25	366	37	4.95	0.00183
Shawinigan Power Company ...	3,750,000	180	30	349	63.5	7.75	0.0027
Glasgow Tramways	2,500,000	75	25	508	56	14.4	0.00232
Yorkshire Electric Power Company	1,500,000	1000	50	122	58.4	8.69	0.00173

The last machine in the above Table is a 1500-kilowatt, three-phase alternator of the Yorkshire Electric Power Company, described in Part V., "Alternators for Steam Turbine Speeds."

All the designs in Table LXXXVIII. are very liberal. One finds, especially in the case of the alternators of Continental manufacturers, considerably higher output co-efficients. These are obtained by working the magnetic circuits at much higher saturations, and by much thinner slot insulations. Neither of these practices should be carried to extremes, as both magnetic and insulating materials are of very variable quality. In the case, however, of some of the alternators in Table LXXXVIII., the thickness of the slot insulation is much greater than is necessary to withstand an insulation test at from two to three times normal voltage from copper to iron.

PART V

ALTERNATORS
FOR STEAM-TURBINE SPEEDS

ALTERNATORS FOR STEAM-TURBINE SPEEDS

Description of a 3-Phase Turbine Generator. 1500-Kilowatt, 11,000-Volt, 6-Pole, 50-Cycle, 1000 Revolutions per Minute Alternator

THIS machine is one of eight built for the Lancashire and Yorkshire Power Companies,[1] and forms part of a Curtis steam-turbine set, the complete sets being built by the British Thomson-Houston Company,[2] through whose courtesy we are enabled to publish this description of the generator.

The generators are mounted on top of the turbine, the rotating field magnets being carried on the upper end of the vertical shaft which runs on a hydraulic footstep-bearing supplied with water at 400 lb. per square inch. Fig. 623, page 534, illustrates one of these machines, half in section and half in elevation.

The stator casing consists of an outer perforated shell of cast iron, 1 in. thick, provided with 18 radial ribs, against which bed the armature laminations, these radial ribs being webbed together with three circumferential ribs of the same thickness.

The laminations are secured by feather keys fitting into dovetail slots in the punchings and parallel slots milled in these longitudinal ribs, and are clamped between two end-plates, the bottom one resting on the casing, and the top one being bolted thereto.

The armature is punched in nine sections, from sheet iron 0.02 in. thick. The slots are wide open, with V grooves in the sides of the teeth to admit of wooden dovetail wedges for securing the armature winding.

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[1] For articles relating to these Companies and description of Power Station, see *Electrical Review*, vol. 57, p. 342, 1905; *Electrical Engineer*, vol. 36, p. 330, 1905.

[2] For articles relating to the Curtis Turbine, see *Electrical Review*, vol. 54, p. 330, 1904; and vol. 57, p. 21, 1905.

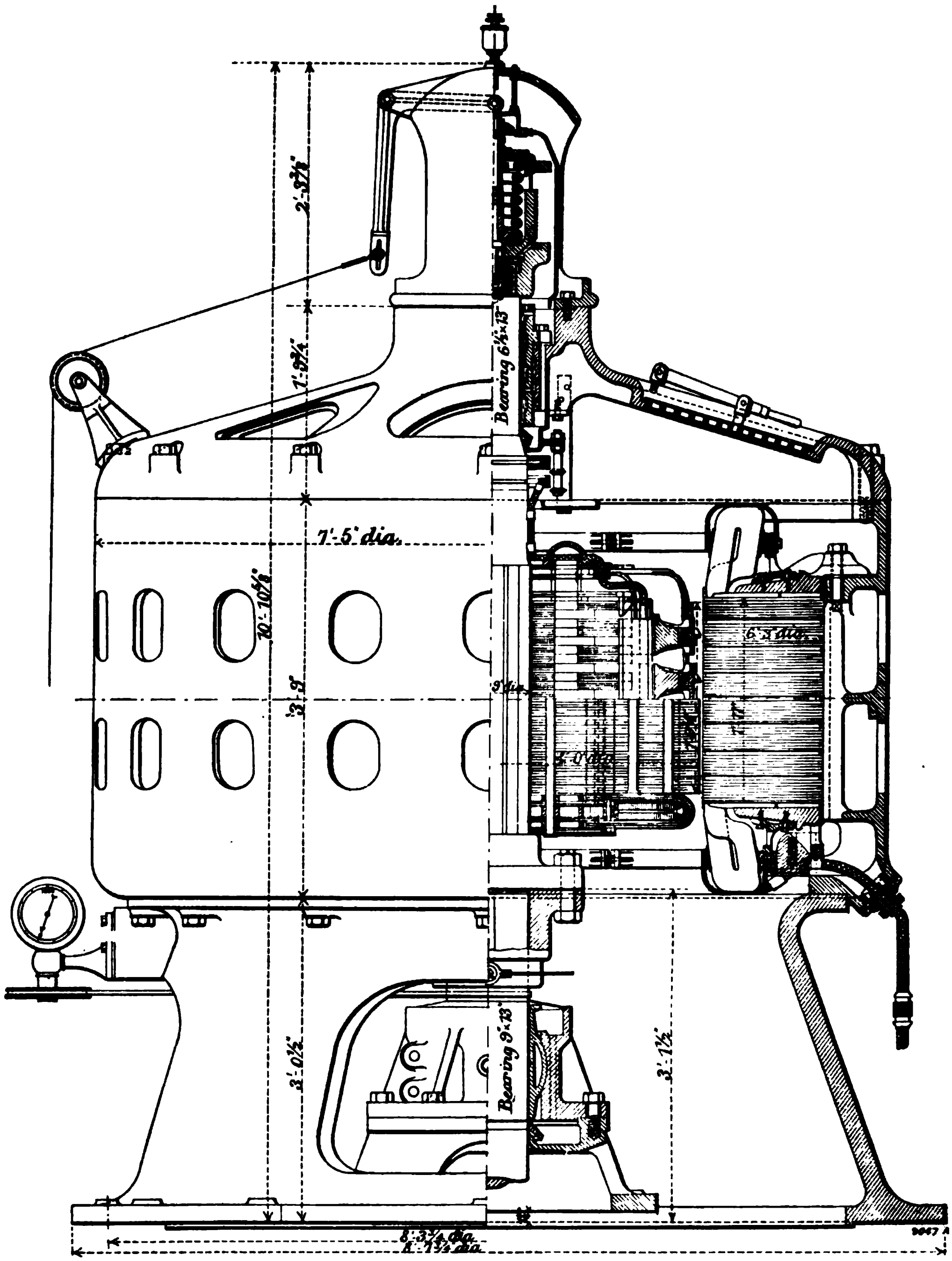


FIG. 623. ELEVATION AND SECTION OF 1500-KILOWATT TURBINE GENERATOR

FIG. 626.

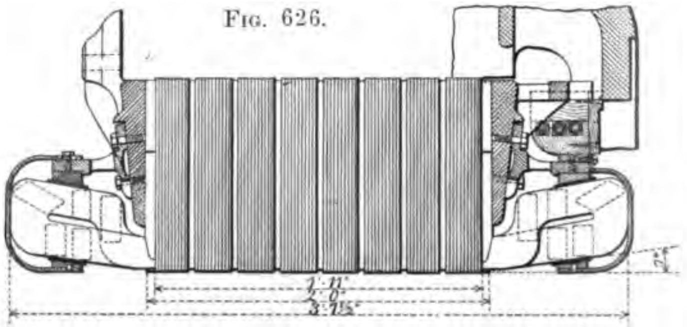
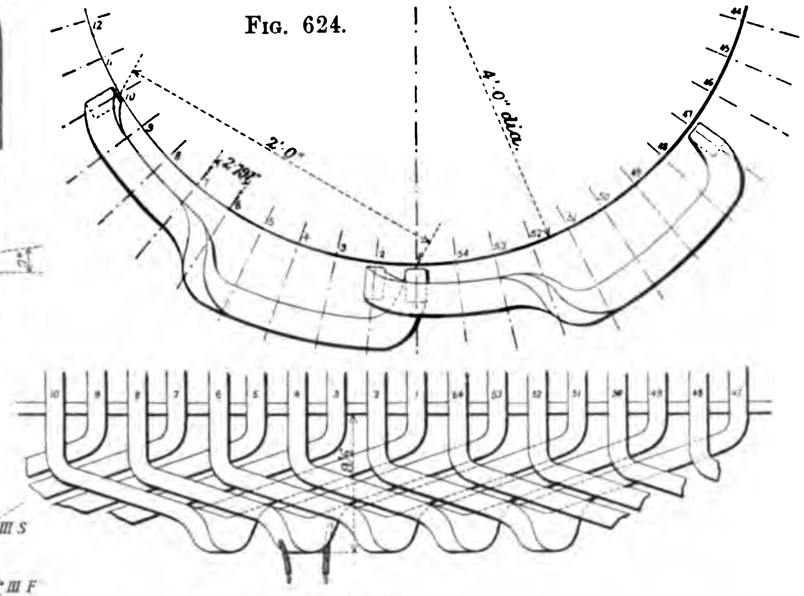


FIG. 624.



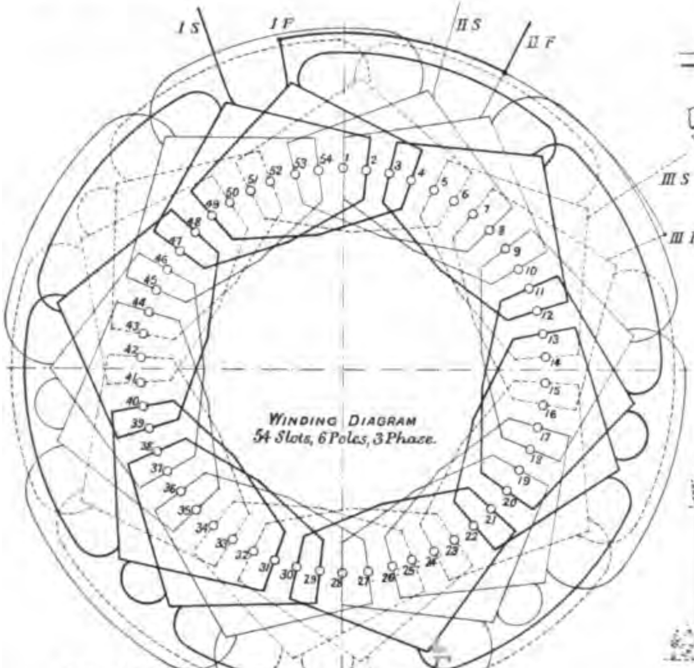


FIG. 625.

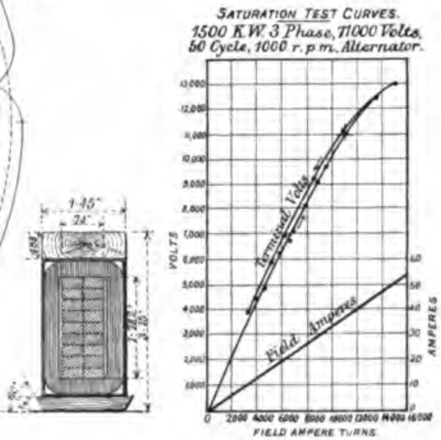


FIG. 635.

FIG. 636.

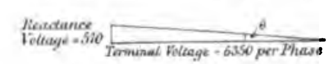
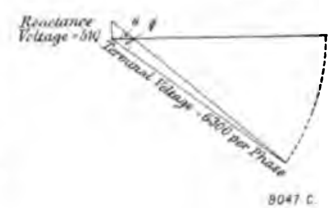


FIG. 637.



FIGS. 624 TO 626. STATOR WINDING

FIG. 635 TO 637. NO-LOAD SATURATION CURVES

The armature winding consists of 27 former wound coils, of shape shown in Fig. 624, Plate X.

The winding is carried out as indicated in Figs. 625 and 626, Plate X., there thus being nine coils of 18 turns each per phase, making 162 turns per phase. The ends of the coils are held against the stator casing by special clamps, embracing the coils and bolted on to the armature end-plates.

The connections from coil to coil are brought round at the back of these clamping blocks, and the terminal cables emerge through bushed holes at the bottom corner of the casing.

The rotor construction is designed to meet the high mechanical stresses set up in the pole-pieces and field windings when rotating at high speeds.

The magnet system is a definite pole construction, having six salient poles, as shown in Figs. 627, page 536, and 633, Plate XII. The whole structure is built up of sheet-iron stampings, constituting a hexagonal hub having two axial T grooves in each of its faces, into which fit correspondingly-shaped projections on the pole-piece stampings, the latter being secured by keys driven in from each end. This arrangement forms a good method of attaching and securing pole-pieces.

The field winding consists of two coils on each pole with a ventilating space $\frac{1}{2}$ in. wide between them, thus increasing the cooling possibilities and allowing higher current densities to be employed.

Each coil is wound with copper strip on edge of section, 1 in. by 0.035 in., with 0.007 in. of insulation between turns.

For convenience in connecting up the coils they are wound alternately right hand and left hand, the beginning of one coil and the end of the next being thus brought out near one another at the same end of the rotor.

The coils are thoroughly secured against any tendency to shift or fly out, in the following manner:—

The coils are clamped between two perforated bobbin flanges, one bedding on the hub and the other on the underside of the pole tip, the overhanging pole tip thus taking up the axial component of the centrifugal force of the sides of the coil.

The lateral component of the centrifugal force of the sides of the coil (*i.e.,* across the pole at right angles to its axis) is taken up by special supporting brackets placed between the poles, and secured

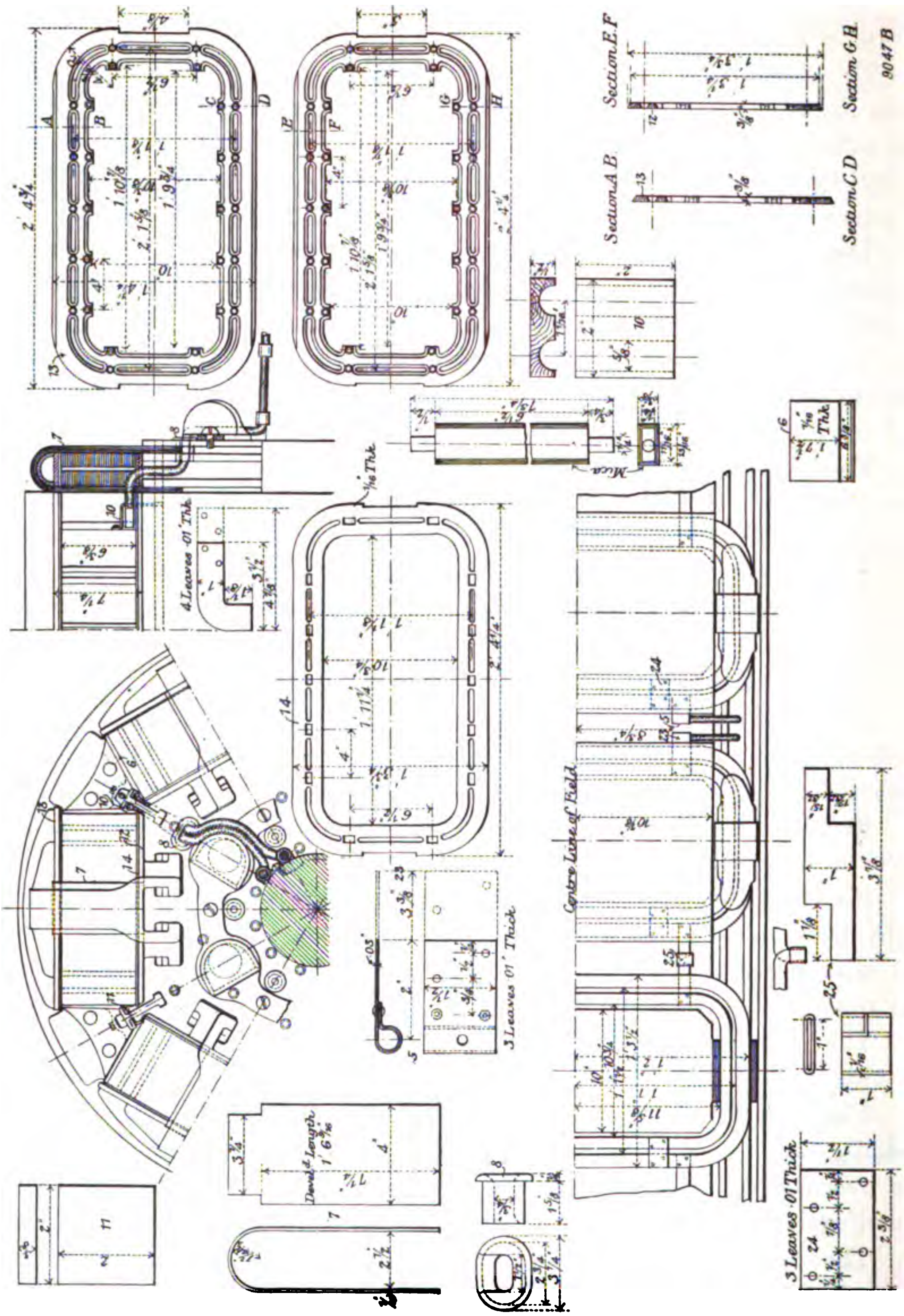


FIG. 627. REVOLVING FIELD MAGNET SYSTEM, AND ARRANGEMENT AND CONNECTION OF FIELD COILS

on to the hub by bolts whose heads engage in grooves formed in the stampings at the corners of the hexagonal hub.

The end portions of the field coils are secured against radial forces by a wrought-iron strap dropped over the coil, and secured at its lower end by projections fitting into the **T** grooves below the pole seat. The wedges which hold the pole pieces also serve for these straps. In this way the field windings are firmly secured against any tendency to shift or bulge, which is most important at these high speeds. The diameter at the pole faces is 47⅛ in., giving a peripheral speed of 12,500 ft. per minute (63 m. per second).

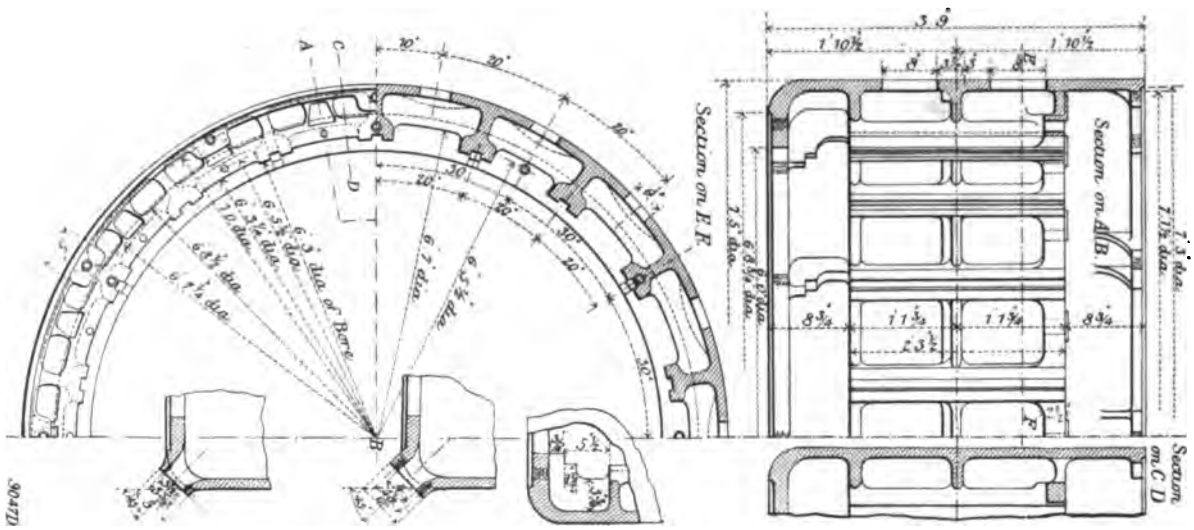


FIG. 628. STATOR FRAME

In Figs. 628 to 631 (see pages 538 to 540) are given drawings of further details of various parts of the machine. Fig. 632, Plate XI., illustrates one of these machines erected, and Figs. 633 and 634, Plate XII., are views of the rotor and stator respectively.

SPECIFICATION FOR 3-PHASE, 1500-KILOWATT ALTERNATOR

Rated output at unity power factor	1500 kilowatts
Number of phases	3
Periodicity in cycles per second	50
Speed in revolutions per minute	1000
Number of poles...	6
Terminal voltage	11,000
Current per terminal at full load	79.5
Connection of armature	Y
Voltage per phase	6350

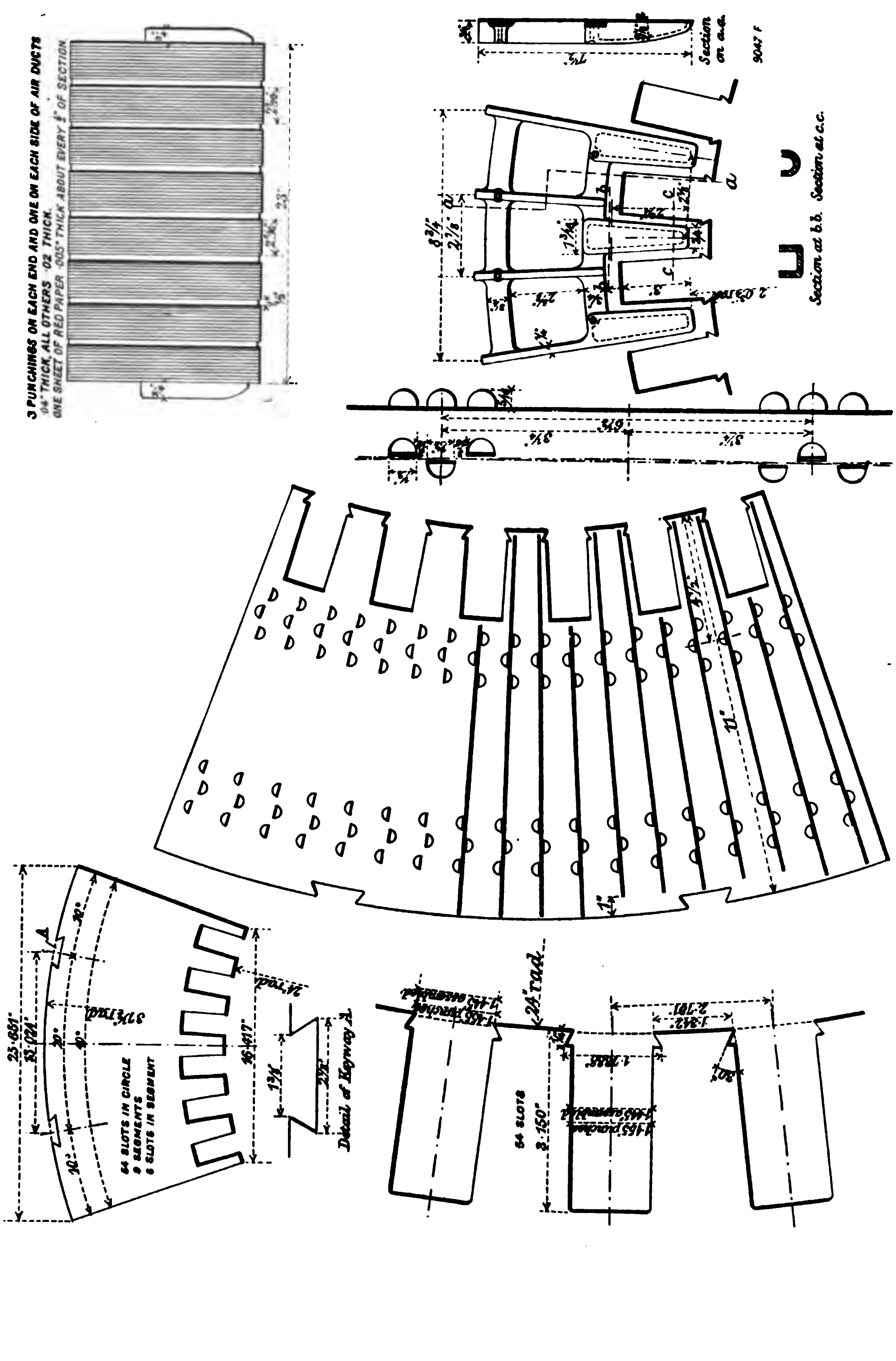


FIG. 629. STATOR PUNCHING AND SPACE BLOCKS

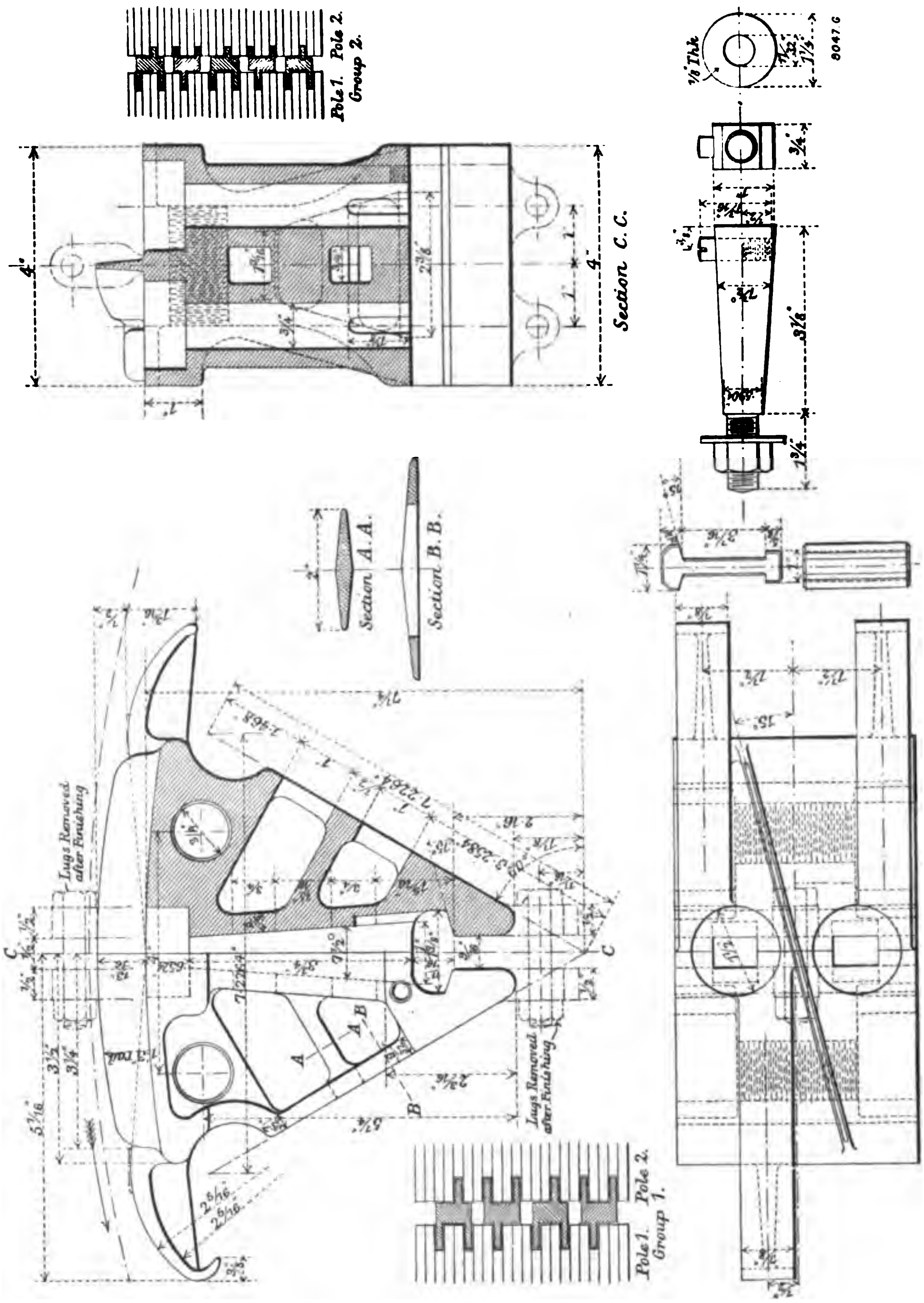


FIG. 630. ADJUSTABLE COIL SUPPORT

Data for Armature Iron:

External diameter of laminations	75 in.
Internal „ „ (at air-gap)	48 „
Gross length of core between flanges	23 in.
Number of slots...	54

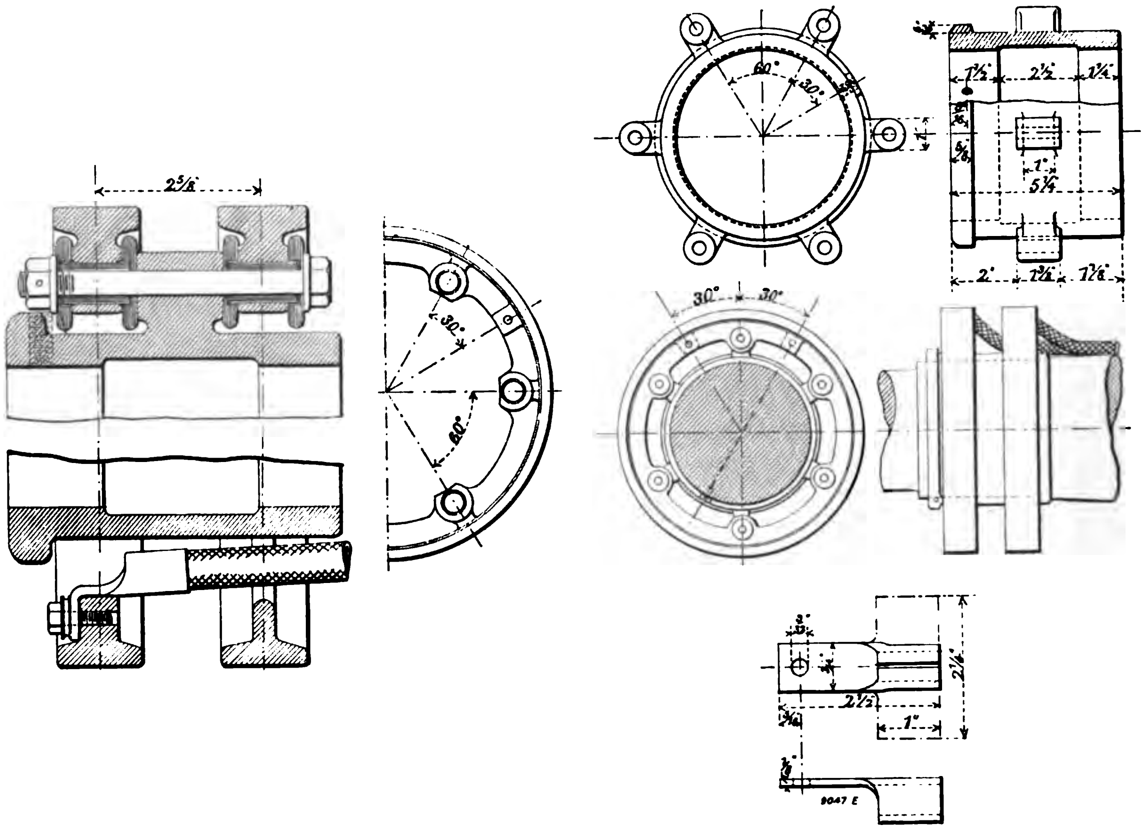


FIG. 631. COLLECTOR

Data for Rotating Field:

Number of poles...	6
Diameter at pole face	47.125 in.
Circumferential length of pole arc	16.6 „
Length of pole piece parallel to shaft	21.75 in.

Data for Armature Winding:

Number of conductors per slot	18
Total number of face conductors	972
Number of conductors per phase	324
„ turns in series per phase	162
„ slots per pole „	3
Nature of conductor	Pressed cable

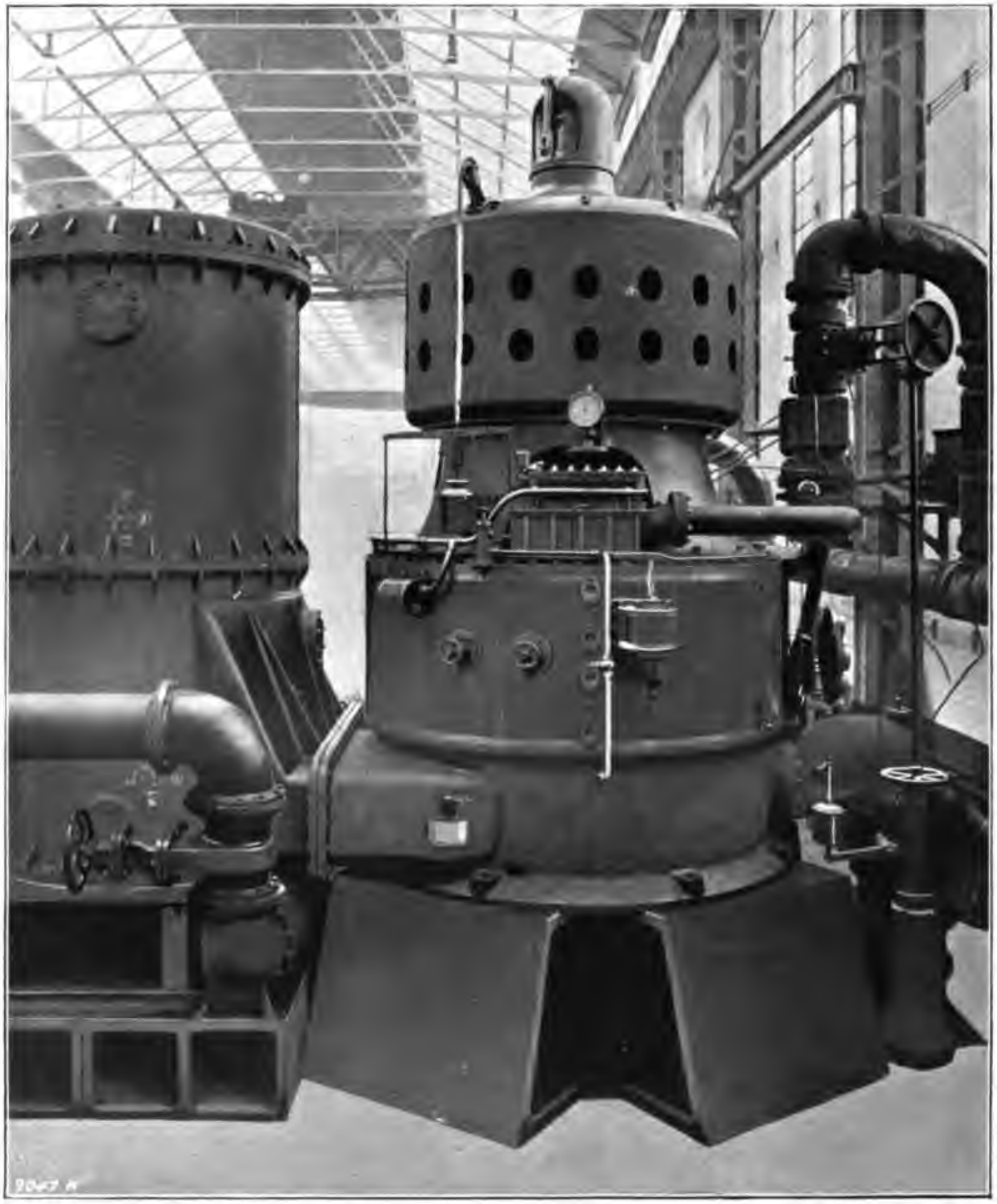


FIG. 632. 1500-KILOWATT, 6-POLE, 11,000-VOLT, 50-CYCLE, 1000 REVOLUTIONS PER MINUTE, 3-PHASE, BRITISH THOMSON-HOUSTON ALTERNATOR

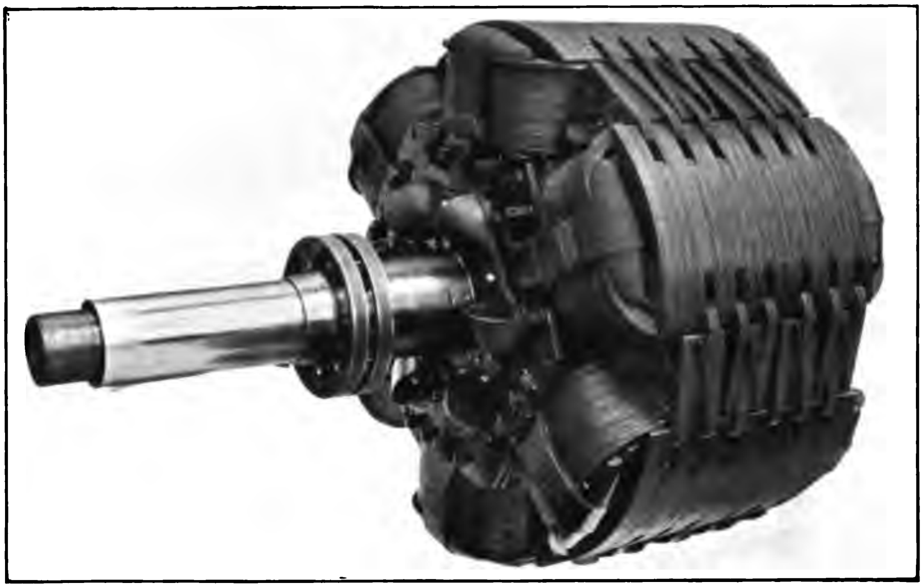


FIG. 633. ROTATING FIELD CONSTRUCTION FOR BRITISH THOMSON-HOUSTON 1500-KILOWATT ALTERNATOR

FIG. 634. STATOR OF BRITISH THOMSON-HOUSTON 500-KILOWATT ALTERNATOR

Dimensions of conductor, bare	0.172 in. × 0.344 in.
Effective cross-section of conductor	0.047 square inch
Current density	1770 amperes per square inch
Arrangement of conductors in slot	9 × 2
Resistance per phase at 20 deg. Cent.	0.338 ohm

Data for Field Winding:

Total number of field coils	12
Number of field coils per pole	2
Turns in series per coil	150
„ „ pole	300
Dimensions of conductor, bare	0.035 in. × 1.0 in.
Resistance of inner coil at 60 deg. Cent.	0.23 ohm
„ outer „ „	0.27 „
„ inner, plus outer	0.5 „
Total resistance of field	3.0 „

Magnetic Data:

Flux in armature	18.4 megalines
Corresponding flux densities in C.G.S. lines per square inch :—	
Armature core	51,000
„ teeth	106,000
Air-gap	52,000
Magnet core	102,000
Yoke	81,500
Leakage coefficient	1.15

Weights:

	lb.
Effective iron, total	17,700
Effective copper, total	2,560
Total weight of effective material	20,260
Pounds of effective material per kilowatt output	13.5

Data from Test Report

The no-load saturation curve taken with increasing and decreasing excitation is shown in Fig. 635, on Plate X., the excitation for normal voltage at no load being 11,000 ampere turns per pole, corresponding to 37 amperes in the field circuit.

The exciting power for 1375 kilowatts non-inductive load at 11,000 terminal volts was 4.5 kilowatts, the exciter voltage being 220.

The machine was run on quarter-load for $1\frac{1}{2}$ hours, half-load for 2 hours, and full load for 3 hours, successively.

After this run the final temperatures observed at various parts of the machine were as follows:—

Rotor spools	...	35 deg. Cent.
Pole tips	...	35 „
Stator winding (back)	...	39 „
„ „ (front)	...	36 „
Core ducts	...	45 „
Teeth	...	44 „

The temperature of the atmosphere was 21 deg., Cent., and the temperature rises were therefore:—

Rotor spools	...	14 deg. Cent.
Pole tips	...	14 „
Stator winding (back)	...	18 „
„ „ (front)	...	15 „
Core ducts	...	24 „
Teeth	...	23 „

The relatively low rises observed after the run point to the results of allowing for a liberal ventilating scheme.

The guaranteed temperature rise in any part of the generator after running on full load at 100 per cent. power factor was not to exceed 30 deg. Cent.

Armature Demagnetisation

Number of turns per phase	...	162
Full-load current „	...	79.5 amperes
Ampere turns „	...	12,900
„ „ per pole	...	2,150
Resultant ampere turns per pole for three phases	...	$2\sqrt{2} \times 2150 = 6100$

Calculation of Armature Inductance

For the slot proportions of this machine we may choose a value of 30 C. G. S. lines, linked with the coil per ampere turn per inch of gross core length.

Number of turns per coil	...	18
Gross core length	...	23 in.
Inductance per coil	...	$18^2 \times 0.00000030 \times 23 = 0.00224$ henrys
Reactance per coil	...	$2\pi \times 50 \times 0.00224 = 0.71$ ohms
„ of 9 coils in series	...	6.4 „
„ voltage	...	$79.5 \times 6.4 = 510$ volts

Excitation for Full Load and Unity Power Factor

In Fig. 636, Plate X., we have

$$\text{Tan } \theta = \frac{510}{6350} = 0.082$$
$$\theta = 4 \text{ deg. } 42 \text{ min.}$$
$$\text{Sin } \theta = 0.082$$

Armature demagnetisation = 6100 sin θ = 6100 × 0.082 = 500
No-load ampere-turns = 11,100
∴ Field ampere-turns for full load at cos ϕ = 1 = 11,600

From the saturation curve, Fig. 635, on the same plate, we find this excitation corresponds to a voltage of 11,650 at no load. Hence inherent regulation =

$$650 \text{ volts} = \frac{650}{11000} \times 100 = 6 \text{ per cent.}$$

Excitation for Full Load at Power Factor = 0.8

In Fig. 637, Plate X., we have $\phi = \cos^{-1}0.8 = 37$ deg. Setting out O V = 6350 volts at 37 deg. to O C, we obtain graphically the value of $\theta = 41$ deg., whence sin $\theta = 0.656$. Hence armature demagnetisation

= 6100 × 0.656
= 4000 ampere-turns
No load ampere-turns = 11,000
∴ Field ampere-turns for full load at cos ϕ = 0.8 = 15,000

From the saturation curve, Fig. 635, we see that this excitation at no load would give a voltage of 13,000. Hence inherent regulation =

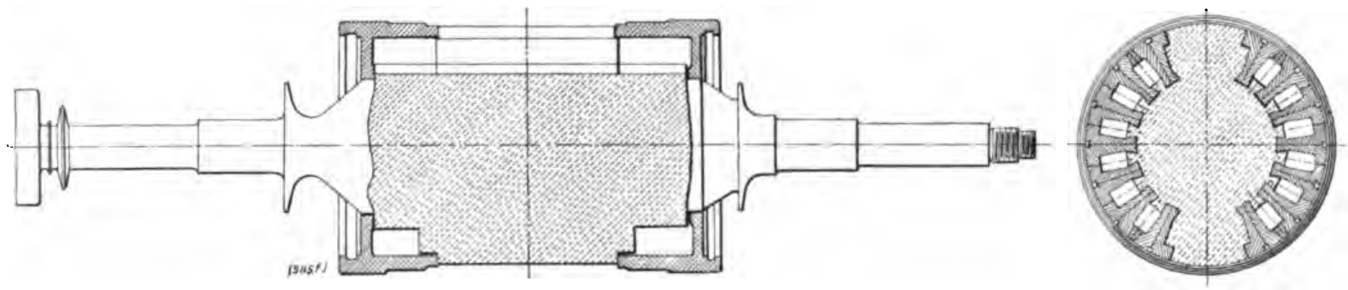
$$2000 \text{ volts} = \frac{2000}{11{,}000} \times 100 = 18 \text{ per cent.}$$

Figs. 638 to 641, Plate XIII., illustrate the construction employed by the Allgemeine Elektricitäts Gesellschaft for the rotors of their turbo-alternator. Fig. 638 is a longitudinal section through the unwound core and end-shields of a 500-kilowatt 3-phase bipolar machine. A cross-section at right angles to the shaft is shown in Fig. 639, from which one sees that shaft and core are constructed from a single casting, into which teeth are dovetailed. The field spools, as may be seen from Fig. 640, are placed in position before the teeth are secured in the dovetailed grooves. Each tooth has two main parts, which are forced laterally into the sides of the dovetails by the insertion of a radial strip, which in turn is retained by a wedge at the surface. Larger

wedges, directly at the upper part of the slots thus formed, assist in securing the windings in place, and in preserving the continuous surface, which is an essential to running at the high speeds employed. In Fig. 641 the end-shields are in place, concealing the winding.

We are indebted to the courtesy of Herrn Geheimrath Rathenau, General Director of the Allgemeine Elektricitäts Gesellschaft of Berlin, for permission to publish these photographs, as well as Figs. 644 to 648, in Part VI., and to Herrn Direktor O. Lasche, the designer of the machines, for supplying them.

PLATE XIII



FIGS. 638 AND 639. SECTION THROUGH ROTOR OF A. E. G. TURBO-ALTERNATOR

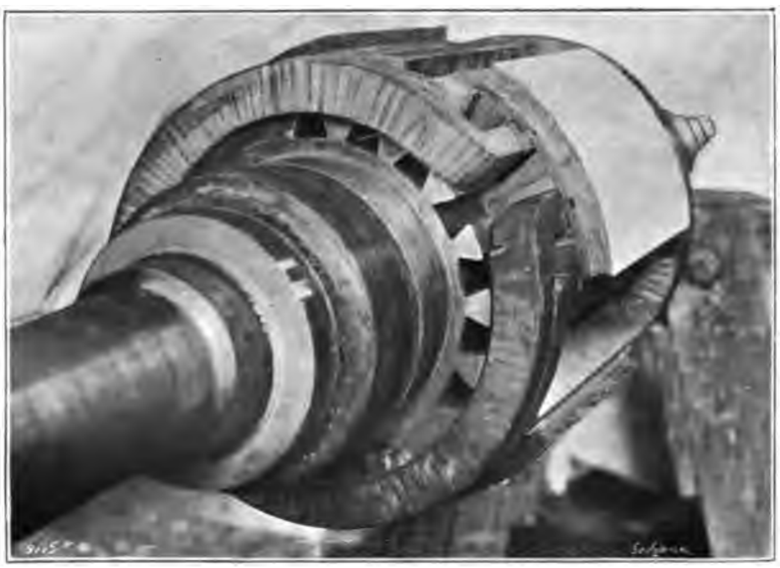


FIG. 640. ROTOR OF A. E. G. TURBO-ALTERNATOR, SHOWING FIELD COILS IN PLACE

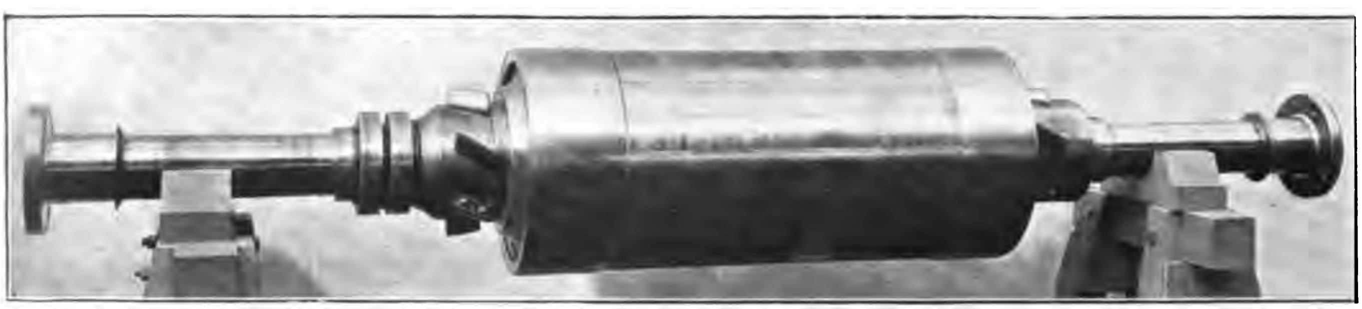


FIG. 641. COMPLETE ROTOR OF A. E. G. TURBO-ALTERNATOR

PART VI

CONTINUOUS CURRENT DYNAMOS FOR STEAM TURBINE SPEEDS

CONTINUOUS - CURRENT DYNAMOS FOR STEAM TURBINE SPEEDS

IN the design of large continuous-current dynamos for steam turbine speeds, it becomes necessary to introduce auxiliary windings in order to obtain satisfactory commutation. Without these provisions it becomes impossible, with fixed brush position for all loads, even with carbon brushes, to avoid proportions leading to reactance voltages which would occasion sparking.

The most satisfactory solution, from the commercial standpoint, consists in the employment of auxiliary poles intermediate between the main poles. These auxiliary[1] poles are furnished with windings carrying the main current, the windings being proportioned to provide a magnetomotive force at any and every load, not only sufficient to neutralise the armature magnetomotive force, but to provide a field of sufficient intensity and extent, and of suitable direction, to approximately neutralise the reactance voltage set up in the armature coils while short-circuited under the brushes.

Such designs afford the best means yet available for securing good commutation in large steam turbine-driven, continuous-current dynamos. The principle is also coming to be widely used in small continuous-current dynamos and motors, not only for high but also for moderate speeds. In cases where heating is the limit of output, and not sparking, such designs are more expensive, and less efficient, and their use is not in accordance with sound engineering practice.

Auxiliary commutating poles are the more suitable the higher the speed, voltage, and output. When all three of these factors are high, a design with such auxiliary poles will alone permit of a satisfactory result. When all three factors are low, a design with commutating poles would be more expensive, and no better as regards commutation, or in any other respect, than a correct design without them. For

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Sometimes called "reversing" or "commutating" poles.

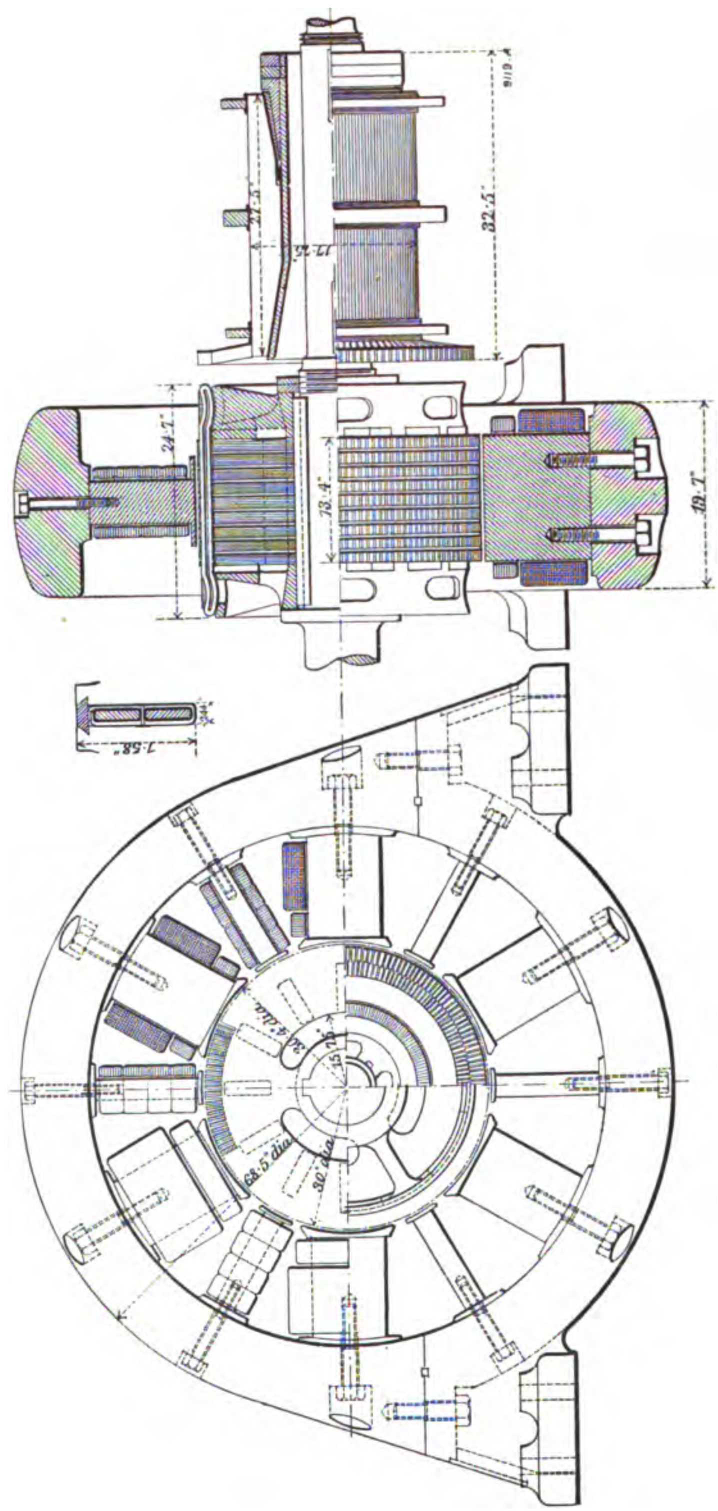

Fig. 642. Outline of General Arrangement of 750-Kilowatt, 250-Volt, 6-Pole, 1500 Revolutions per Minute, Continuous-Current Generator

intermediate cases a careful preliminary comparison of alternative designs is often necessary.

For a 750-kilowatt, 250-volt, 1000-revolutions per minute design, auxiliary poles should be employed, as an ordinary design with good commutation is impossible. For 250-kilowatt machines for 250 volts and 1000 revolutions per minute, while designs with commutating poles are much cheaper and more satisfactory, good designs without them are still practicable.

Coming down to 100-kilowatt machines for 250 volts at 1000 revolutions per minute, the advantage which commutating-pole designs have over ordinary designs is but slight. At a somewhat lower output or

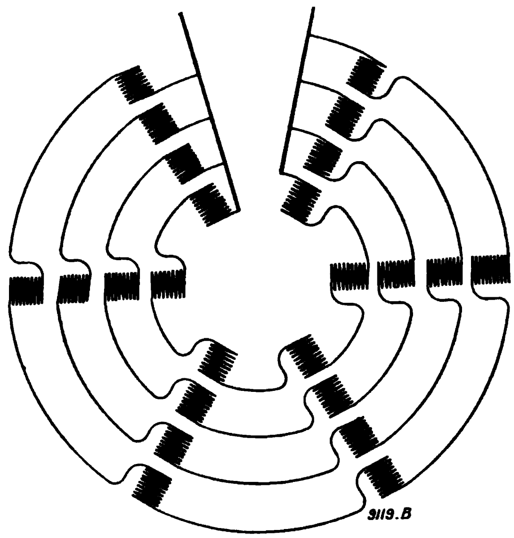

Fig. 643. Winding Scheme for Auxiliary Poles

speed there would, for 250-volt designs, be no choice. For still lower outputs and speed—for 250 volts—the commutating-pole design becomes the more expensive. For a 100-revolutions per minute machine for 250 or even 500 volts, the preferable design would be without commutating poles, even in large capacities. At 200 revolutions per minute and 500 volts, commutating poles are desirable from, say, 400 kilowatts upwards; and for 200 revolutions per minute and 250 volts, from, say, 600 kilowatts upwards.

Of course, such statements can only be general, and the preferable design depends very greatly upon the precise conditions for which the machine is to be used. In general, however, when heating and not commutation is the limiting consideration, the cheapest and best design

will be without commutating poles, and *vice versâ* when commutation is the limit. Commutating poles are generally preferable to Déri windings, on the score of the mechanical superiority and lower labour cost associated with the windings of the former type.

In the following specification, and in the diagrammatic sketches in Figs. 642 and 643, pages 548 and 549, are given the rough outlines for the electromagnetic design for a 750-kilowatt, 250-volt continuous-current generator, for a speed of 1500 revolutions per minute.

Specification of 750-Kilowatt, 250-Volt, 1500 Revolutions per Minute Continuous-Current Generator

Armature:

The core-plates are stamped in one piece from plates not more than 0.5 millimetres thick, and are assembled directly upon the shaft, as the required shaft diameter does not permit of an intermediate armature spider. The slot conductors are kept in place by wedges, which in turn are retained by recesses in the sides of the slot, and by binding bands. The end connections are carried on a specially-shaped end-plate, which is curved on its surface, and permits of heaping towards the centre the binding wire holding the end connections.

Commutator:

The construction of the commutator differs rather radically from that customarily employed for slow and moderate speed designs.

The segments are built up with the intervening layers of mica and clamped together. Circumferential mica bands are then placed at the middle and at the two ends, and three steel rings are shrunk on over the mica. The interior contour is then machined, and the commutator is secured in place on its sleeve by cones forced in by end-rings. The external surface is then turned. Ventilation of the inside of the commutator is provided for by three channels inside the spider, through which air can be driven by cup-shaped fans at the outer end of each channel.

Brushes:

The brushes are of carbon, or preferably of graphite, of low contact and radial resistance, and high transverse resistance. They are carried in holders of such type as to prevent vibration and chattering at the high peripheral speed employed.

Magnet Frame:

The yoke is made from cast iron. This is employed chiefly on account of the greater rigidity and stability thereby obtained, as compared with a cast-steel yoke of equivalent magnetic capacity.

Auxiliary Commutating Poles:

The main current of this machine is equal to 3000 amperes. Taking 1000 amperes through a diverting shunt leaves 2000 amperes, which, if carried through the coils of the six auxiliary poles in a single series, would require about five turns per pole, and each turn would be of inconveniently large cross-section. It is also

objectionable to use many turns in parallel, owing to the difficulty of obtaining good contact at the connections. An alternative would be to put the spools in parallel, but unless very carefully adjusted, the different windings would be of unequal resistance, resulting in varying strengths of current in different spools.

To overcome these difficulties the following arrangement of winding has been adopted: Each spool is subdivided into four sections, each wound with 5½ turns of copper strip. The details of the winding scheme are shown diagrammatically in Fig. 643.

The winding is arranged in four parallel circuits with 500 amperes per circuit. Each circuit contains one section of winding on each pole, or 33 turns in series. By this arrangement, the convenience of parallel winding is obtained, without incurring the liability of having varying strengths of field on the different commutating poles, since any inequality in the current in one section is shared by all the poles.

Designing Data for 750-Kilowatt 250-Volt, 1500 Revolutions per Minute, Continuous-Current Generator

Description

Number of poles...	6
Kilowatts output at rated load	750
Speed in revolutions per minute	1500
Frequency in cycles per second	75
Terminal voltage	250
Amperes output at full rated load	3000

General Dimensions

Armature:

External diameter of laminations	30 in.
Diameter at bottom of slots	26.8 „
Internal diameter of laminations	15.75 „
Gross length of core between flanges	13.4 „
Number of ventilating ducts	8
Width of each duct	0.395 in.
Percentage insulation on core plates	10 per cent.
Effective length of core	9.2 in.
Number of slots...	162
Depth of slot	1.58 in.
Width of slot, stamped	0.256 „
„ „ assembled	0.244 „
Average width of tooth	0.29 „

Magnet Core:

Length of pole face parallel to shaft	13.4 „
Mean length of pole arc	9.4 „
Width of magnet core parallel to shaft	13.4 „
„ „ „ at right angles to shaft	7.9 „
Thickness of pole shoe at centre of arc	0.394 „
Radial length of magnet core	11.0 „
„ depth of air gap	0.236 „

Yoke :

External diameter	68.5 in.
Internal „	54.5 „
Thickness of yoke	7.1 „
Axial width	19.7 „

Reversing Pole Core :

Length of pole face parallel to shaft	9.5 „
„ „ arc	2.9 „
Radial depth of air gap	0.275 „
Width of core parallel to shaft	5.7 „
„ „ at right angles to shaft	2.56 „
Cross section of core	13.2 sq. in.

Electrical Data :

Number of face conductors	324
„ slots	162
„ conduotors per slot	2
Style of winding	6-circ. double
Number of circuits through armature	12
Total amperes from commutator	3000
Amperes per circuit	250
Mean length of one turn	74 in.
Turns in series between brushes	13.5 „
Total length of conducting path between brushes	995 „
Height of bare conductor	0.59 „
Width „ „	0.157 „
Cross section of one conductor	0.093 „
„ „ of all parallel conductors	1.12 sq. in.
Resistance of armature winding from positive to negative brushes at 60 deg. Cent.	.0007 ohms

Commutator Calculations :

Commutator diameter	17.75 in.
Number of segments	162
Thickness of segment + insulation at periphery	0.344 in.
Total length of commutator	27.5 „
Number of sets of brushes...	6
„ brushes per set	12
Width of brush	1.34 in.
Length of arc of contact	1.025 „
Contact surface per brush...	1.37 sq. in.
Amperes per square inch of brush contact surface	61
Peripheral speed of commutator in feet per second	116
Reactance voltage	15.5

Magnetic Data :

Terminal voltage at rated output	250 volts
Total induced voltage at rated output	256 „
Flux entering armature per pole at rated full load megalines ...	6.32
Leakage factor for main magnetic circuit	1.35
Flux generated per pole at rated full load megalines	8.5

Ampere Turns Required for Full Load Voltage at No Load

	Density in Lines per Square Inch.	Total Ampere Turns
Armature core	62,000	68
„ teeth	142,000	2200
Air-gap	50,500	3760
Magnet core	92,000	1050
„ yoke	33,600	1130
Total ampere turns for full load voltage at no load ...		8208
Ampere turns provided by shunt winding		8000
„ „ „ by series winding		2400

Magnetising Winding Calculations

Shunt Spool:

Axial length of winding	7.1 in.
Depth of winding	2.36 „
Gauge number of conductor	B.W.G. 12
Amperes in the winding	8.2
Current density in amperes per square inch	870 sq. in.
Watts lost per spool	242
Weight of copper per shunt spool	131 lb.

Series Spool:

Dimensions of conductor	1.57 × 0.197 in.
Number in parallel	6
Total cross section	1.86 sq. in.
Number of turns per spool	1.5
Current in winding	1600
„ density in amperes per square inch	860
Watts lost per spool	79
Weight of copper per spool	45 lb.

Reversing Pole Winding:

Number of sections of winding	4
Turns per section	$5\frac{1}{2}$
Dimensions of conductor	1.18 × 0.177 in.
Number in parallel	2
Cross section of one turn	0.42 sq. in.
Watts lost per section	57
Weight of copper per spool (for four sections)	65 lb.

Armature Losses

Copper Loss:

Total amperes from commutator	3000
Resistance of winding from positive to negative at 60 deg. Cent. temperature rise	0.00070 ohms
Watts lost in armature winding	6250
Weight of armature copper	365 lb.

Iron Loss:

Total weight of laminations	1142 lb.
Flux density in core (kilolines per square inch)	62
Periodicity in cycles per second	75
Total core loss, watts	12,000
Friction and windage losses, watts	3000

Heating:

Armature watts lost per square inch	8.0
Commutator watts lost per square inch	7.4
Shunt spool " "	0.66
Series spool " "	0.62
Reversing pole spool watts lost per square inch	0.81

Total Losses:

Total constant losses	22,782 watts	
" variable losses	16,442 "	
Total	39,224 "	
Commercial efficiency at full load		95.2 per cent.

WEIGHTS OF EFFECTIVE MATERIALS

Armature copper	365 lb.
Commutator copper	1210 "
Shunt spool copper	790 "
Series spool copper	258 "
Reversing pole spool copper	352 "
Armature laminations	1150 "
Magnet cores, cast steel	1760 "
Reversing pole cores, cast steel	187 "
Yoke, cast iron	6500 "
Total weight of effective material	12,572 lb.

COSTS OF EFFECTIVE MATERIAL

Total cost of effective copper	2700 shillings
" " iron	1164 "
" all effective material	3864 "
" effective material per kilowatt output	5.15 "

The output coefficient for this machine,

$$\phi = \frac{\text{Watts output}}{(\text{Armature diameter in centimetres})^2 \times \text{Core length in centimetres} \times \text{speed in R.P.M.}}$$

$$= \frac{750{,}000}{(30 \times 2.54)^2 \times 13.4 \times 1500} = 0.00252.$$

NOTE.—This design was worked out in metric units which have been converted into inches to preserve uniformity throughout the book. This will explain the unevenness of some of the dimensions.

As will be seen from an examination of the design, a high periodicity (in this case 75 cycles per second) is unavoidable. As a fairly high-core density is also necessary, in order, in spite of the restricted diameter, to provide access for sufficient air to the interior of the core, thence to flow radially outward through the ventilating ducts, a rather high core loss per pound of armature laminations must necessarily be permitted. Liberal provision of radial ventilating ducts must therefore be made, as the total rate of generation of heat in the armature per square inch of peripheral radiating surface will be much higher than is otherwise permissible.

The main problem, however, relates to the design of the commutator. Notwithstanding recent very encouraging progress in the development of improved carbon and graphite brushes, and in improved brush-holders, a peripheral speed of 35 meters (115 ft.) per second is as high as it is yet desirable to go. In order to get sufficient radiating surface to prevent excessive temperature rise, the commutator, as will be seen from the example, is of great length, and correspondingly awkward as regards mechanical design, the more especially so with respect to providing internal ducts for the circulation of air. As a compromise between the mechanical and electrical difficulties, a much higher temperature rise than would be preferred has been allowed in this design. The temperature rise will be some 60 deg. Cent. Some designers would have shortened the commutator by resorting to copper brushes. This, in the writers' opinion, is not advisable. The newer types of graphite brushes indicate very encouraging progress toward lower friction coefficients, and I^2R contact losses; and this progress, when thoroughly verified by time tests, can gradually be followed up by decreased commutator lengths.

The design above set forth will serve to illustrate certain important points arising in connection with the calculation of machines of this type.

The leakage coefficient must be taken much higher than in the calculation of ordinary designs, without reversing poles. Obviously, this applies to a greater degree to the magnetic circuit of the reversing poles than to the main magnetic circuit. In the design which we have illustrated, the leakage coefficient has been taken equal to 1.35 for the main magnetic circuit, and to 1.45 for the auxiliary circuit; for while the leakage flux from the auxiliary circuit has available the large surfaces

of the main circuit, the leakage flux from the main circuit is only increased by the small extent caused by the comparatively limited surfaces of the auxiliary poles.

As the exciting coils on the auxiliary poles are mainly required for overcoming the armature magnetomotive force of 6550 ampere turns per armature pole, one cannot save much copper by employing low densities or short air-gaps in the auxiliary circuits. In this design the air-gap (0.275 in.) accounts for 3800 ampere-turns, and the pole core saturated to 98,000 lines per square inch, for 1200. The total ampere-turns are 11,600, of which the armature magnetomotive force is 56 per cent. A deep air-gap will tend to reduce the core loss, and also the noise. Of less, but still of considerable importance, is the fact that a deep air-gap, under the reversing poles will, by reason of the magnetic material of the pole shoe being further removed from the armature conductors, increase the magnetic reluctance of the inductive iron paths round the short-circuited armature coils, and will thus slightly reduce the reactance voltage, and in turn the dimensions of the reversing pole.

The calculation of the necessary flux entering the armature from the auxiliary pole is derived in the following way :—

Let l = the length of embedded conductor lying within the region of the flux issuing from the pole, *i.e.*, the length of conductor which actually cuts the auxiliary field.

This length will be equal to the breadth of the pole shoe, parallel to the shaft b, multiplied by 1.1 to allow for fringing of the field at pole tips, and by 0.7, because, of the total length of a face conductor, only about 0.7 of it is "active" or "embedded" in armature iron, the remaining 0.3 being taken up by air ducts and core insulation. Hence, $l = 1.1 \times 0.7 \times b = 0.77\, b$. If S = the peripheral speed of armature in centimetres per second, and B the average density in the air-gap of the auxiliary pole in C.G.S. lines per square centimetre, then the rate of cutting of flux by one conductor is equal to

$B \times l \times S$ = C.G.S. lines per second, and the electromotive force generated in this conductor is

$$\frac{B \times l \times S}{10^8}.$$

Since we have two conductors in the short-circuited turn, the electromotive force generated in this turn is equal to

$$\frac{2\,B\,l\,S}{10^{\circ}}.$$

This electromotive force must be sufficient to neutralise the reactance voltage.

If v = the mean reactance voltage

$$\left(=\frac{\text{Reactance voltage}}{\frac{\pi}{2}}\right)$$

Then we have

$$v=\frac{2\,\mathrm{B}\,l\,\mathrm{S}}{10^8}.$$

Whence

$$\mathrm{B}=\frac{v\times 10^8}{2\,l\,\mathrm{S}},$$

which determines the requisite flux density at the pole-face.

The length of the pole-arc of the auxiliary pole is chosen such that during the whole period of commutation a coil shall be moving in the auxiliary field.

It is important that the coil shall be moving in a sufficient field at the moment when its commutator segments are leaving the brushes. The pole-arc should cover as many slots as are carrying conductors simultaneously short-circuited by the brush, and it is safer to have a slightly larger pole-arc than this to allow for any distortion of the auxiliary field, which may occur with varying load. An additional allowance is also necessary when there are several segments per slot, as the true diameter of commutation is then constantly swinging back and forth through a small arc.

The total flux crossing the gap per auxiliary pole may now be deduced from the dimensions of the pole-face. The total flux generated in the pole is this quantity multiplied by the leakage coefficient of the auxiliary circuit, referred to above. The total ampere turns required on the auxiliary pole are made up of a number equivalent to the magnetomotive force of the armature, and a number of ampere turns sufficient to send the flux across the auxiliary air-gap and round the auxiliary magnetic circuit—*i.e.*, through the pole core and teeth immediately under the pole-face. As this saturation component of the ampere turns, in the design here given, at any rate, is comparatively small compared with the armature reaction component, the total ampere turns on the pole will not be much increased by saturating the pole core to a fairly high value, thus reducing the cross-section of pole to a minimum, and consequently the peripheral length of the winding, and obtaining

a minimum weight of copper. Such high saturation has, of course, the objection that since the reactance voltage increases directly with the output, so should also the reversing field from the auxiliary pole; but it must be remembered that exact equality need not be maintained at all loads, since a range of residual voltage from one or two volts negative to one or two volts positive—*i.e.*, a total range of, say, three volts—will not suffice to occasion sparking.

The resistance of the diverting shunt is finally adjusted during actual test, to such a value as to obtain good commutation at all loads.

There has been a tendency to envelope in mystery these very simple calculations, and the clear exposition of Dr. Breslauer ("Elektrotechn. Zeitschr.", Heft 28, July 13th, 1905, page 640) is, therefore, all the more welcome.

As pointed out by Dr. Breslauer in the article just referred to, the principle involved is very old, and is due to Menges, Swinburne, Fischer-Hinnen, and others. Dr. Breslauer points out that Menges' patent was granted in 1884, and that Fischer-Hinnen's descriptions date from 1891.

The Allgemeine Elektricitäts Gesellschaft of Berlin prefer the so-called Déri winding to the use of auxiliary poles as above described. The field of a 4-pole, 300-kilowatt, 230-volt, continuous-current turbo-dynamo of their standard construction, employing the Déri winding, is reproduced from a photograph in Fig. 644, Plate XIV., which represents the stage of manufacture at which the compensating winding has been completed. This compensating winding is connected in series with the armature. Were it distributed over the entire periphery, it would completely neutralise all armature interference with the magnetic field set up by the four main field coils, three of which are shown in place in Fig. 645, Plate XIV. As a matter of fact, the compensating winding is proportioned for a slightly greater magnetomotive force than that exerted by the armature winding. The excess magnetomotive force impels a magnetic flux through so-called "reversing" lugs, which are shown in place in Figs. 645 and 646, Plate XIV., being retained in dovetailed grooves seen in Fig. 644. The magnetic flux entering the armature by the reversing lugs is proportioned to neutralise the reactance voltage, which would otherwise be set up in the short-circuited armature coils.

Fig. 644 represents, as stated, the frame of a 230-volt, 300-kilowatt

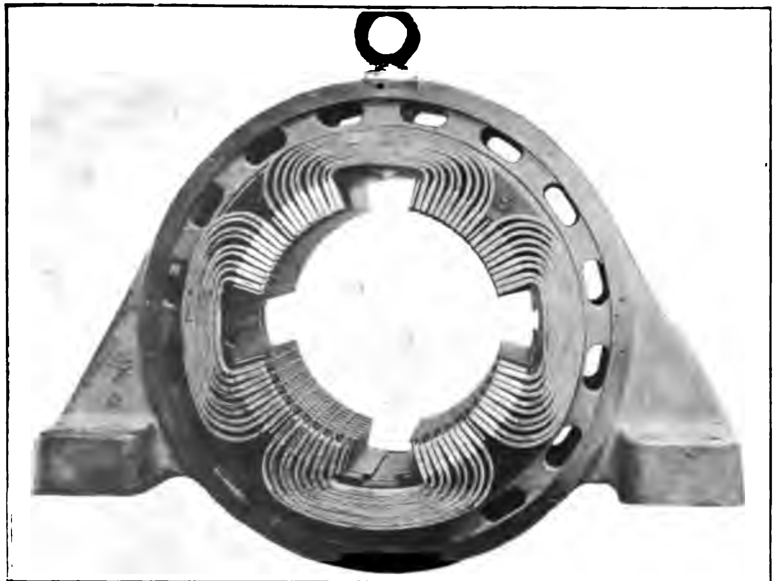

FIG. 644. A. E. G. 300-KILOWATT, 230-VOLT DYNAMO, WITH DÉRI WINDING IN PLACE

FIG. 645. A. E. G. 100-KILOWATT, 550-VOLT DYNAMO, WITH 3 OF 4 FIELD COILS IN PLACE

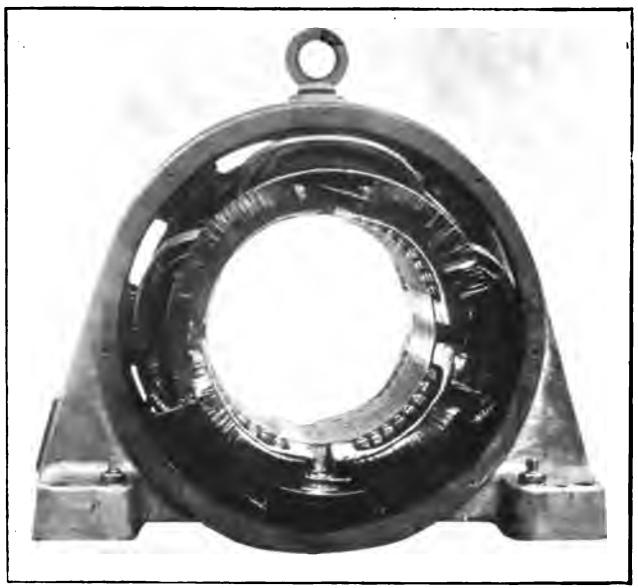

FIG. 646. COMPLETE WOUND STATOR OF A. E. G. 100-KILOWATT, 550-VOLT DYNAMO, WITH DÉRI WINDINGS

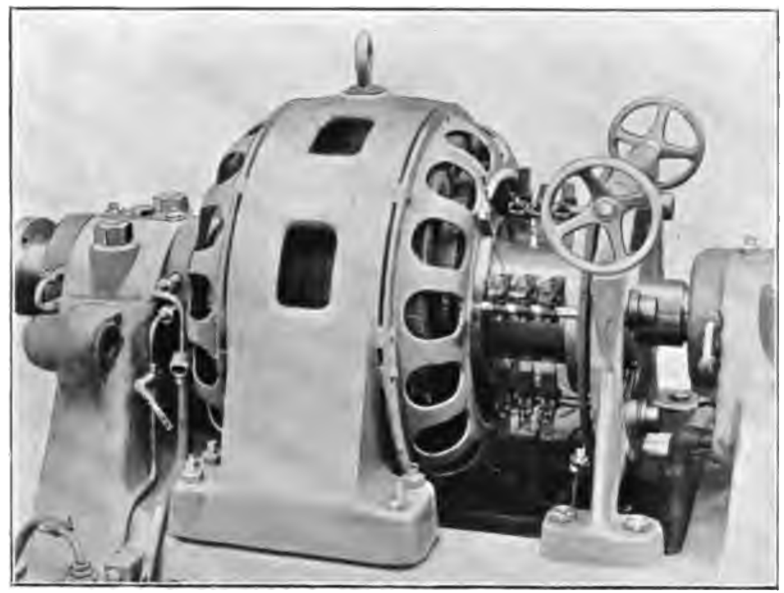

FIG. 647. A. E. G. CONTINUOUS-CURRENT TURBO-DYNAMO

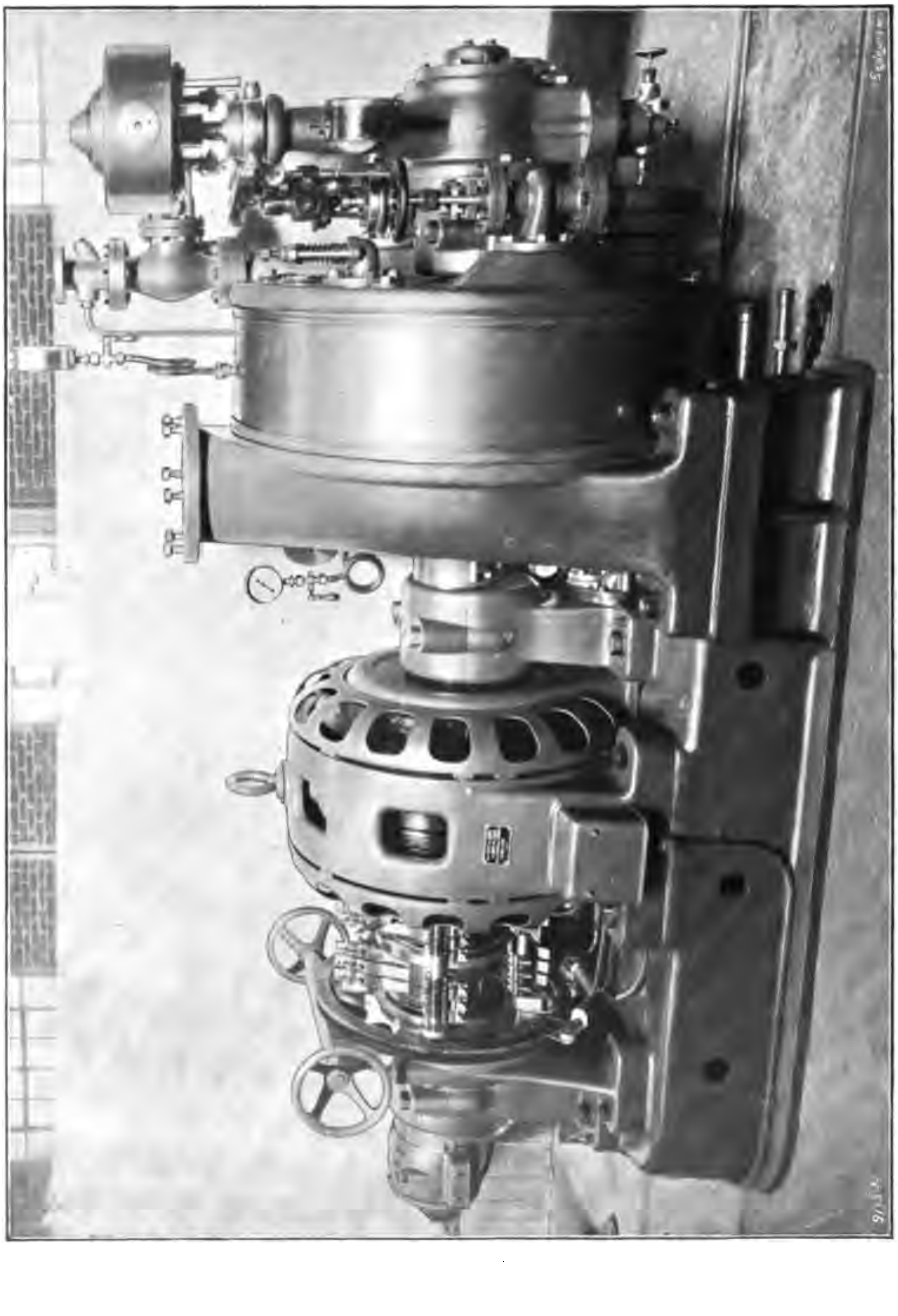

FIG. 648. 65-KILOWATT DIRECT-CURRENT TURBO-DYNAMO. SPECIAL TYPE FOR GERMAN IMPERIAL NAVY

machine. In this case the compensating winding is constructed with a single rectangular conductor per slot, since the main current at full load amounts to 1300 amperes. But Figs. 645 and 646 relate to a 550-volt, 100-kilowatt machine, with a full load current of only 182 amperes. In this case the compensating winding consists of coils, each comprising several turns of round wire. The Allgemeine Elektricitäts Gesellschaft recommends separate excitation for their continuous-current turbo-dynamos, as satisfactory regulation is not practicable with self-excitation, owing to their particular magnetic properties. Fig. 647, Plate XIV., is a view of a machine of this type with the commutator in place.

A 65-kilowatt continuous-current turbo-generating set of special type, as supplied by the Allgemeine Elektricitäts Gesellschaft to the German Imperial Navy, is shown in Fig. 648, Plate XV.

APPENDIX

4 c

APPENDIX

TABLE LXXXIX.—PROPERTIES OF COMMERCIAL COPPER WIRE

Brown and Sharpe Wire Gauge (B. and S.)

Gauge Number.	Diameter (Inches). Bare.	S. C. C.	D. C. C.	T. C. C.	Cross Section. (Sq. In.)	Gauge Number.	Ohms per 1000 Ft. 0 deg. C.	20 deg. C.	40 deg. C.	60 deg. C.	80 deg. C.	100 deg. C.	Gauge Number.	Feet per Ohm at 20 deg. C.	Pounds per Ohm at 20 deg. C.	Feet per Pound.	Pounds per 1000 Ft. (Bare.)
0000	.460	..	..	.480	.166	0000	.0452	.0489	.0526	.0565	.0606	.0643	0000	20400	13100	1.56	641
000	.410	..	..	.430	.132	000	.0570	.0617	.0663	.0713	.0764	.0812	000	16200	8230	1.97	508
00	.365	..	..	.335	.105	00	.0720	.0778	.0837	.0900	.0963	.102	00	12900	5180	2.48	403
0	.325	..	..	.343	.0829	0	.0909	.0981	.106	.113	.122	.129	0	10200	3260	3.13	320
1	.289	..	.303	.307	.0657	1	.115	.124	.134	.144	.153	.162	1	8080	2050	3.95	253
2	.258	..	.272	.276	.0521	2	.144	.156	.168	.180	.193	.204	2	6410	1290	4.98	201
3	.229	..	.243	.247	.0413	3	.182	.197	.212	.228	.244	.258	3	5080	810	6.28	159
4	.204	..	.216	.220	.0328	4	.230	.248	.268	.288	.307	.325	4	4030	509	7.91	126
5	.182	..	.194	.198	.0260	5	.290	.313	.337	.362	.387	.410	5	3200	320	9.98	100
6	.162	..	.174	.178	.0206	6	.365	.394	.425	.456	.488	.516	6	2540	202	12.6	79.5
7	.144	..	.156	.160	.0163	7	.460	.497	.535	.576	.617	.655	7	2010	127	15.9	63.0
8	.128	..	.140	.144	.0129	8	.582	.628	.677	.728	.780	.828	8	1600	79.7	20.0	50.0
9	.114	..	.126	.130	.0103	9	.732	.791	.852	.915	.979	1.04	9	1270	50.1	25.2	39.6
10	.102	.108	.112	.116	.00815	10	.924	.997	1.08	1.16	1.24	1.32	10	1000	31.5	31.8	31.4
11	.0907	.097	.101	.105	.00647	11	1.17	1.26	1.36	1.47	1.56	1.65	11	795	19.8	40.1	24.9
12	.0808	.087	.091	.095	.00513	12	1.47	1.59	1.71	1.84	1.96	2.08	12	631	12.5	50.6	19.8
13	.0720	.078	.082	.086	.00407	13	1.85	2.00	2.16	2.32	2.47	2.63	13	500	7.84	63.8	15.7
14	.0641	.071	.075	.078	.00323	14	2.33	2.52	2.71	2.92	3.13	3.32	14	397	4.93	80.4	12.4
15	.0571	.063	.068	.071	.00256	15	2.94	3.18	3.42	2.68	3.94	4.18	15	315	3.10	101	9.86
16	.0508	.055	.059	.063	.00203	16	3.72	4.01	4.33	4.65	4.96	5.25	16	249	1.95	128	7.82
17	.0453	.049	.053	.057	.00161	17	4.70	5.06	5.45	5.87	6.26	6.62	17	198	1.23	161	6.20
18	.0403	.044	.048	.052	.00128	18	5.90	6.37	6.87	7.38	7.89	8.35	18	157	.772	208	4.92
19	.0358	.039	.044	.047	.00102	19	7.45	8.04	8.66	9.30	9.95	10.6	19	124	.485	257	3.90
20	.0320	.036	.040	.044	.000805	20	9.39	10.1	10.9	11.7	12.6	13.4	20	98.7	.305	323	3.10
21	.0285	.032	.036	.040	.000639	21	11.8	12.8	13.7	14.8	15.8	16.8	21	77.5	.192	408	2.45
22	.0253	.029	.033	.037	.000502	22	15.1	16.3	17.6	11.9	20.0	21.2	22	62.1	.121	514	1.95
23	.0226	.027	.031	.035	.000402	23	18.8	20.3	21.9	23.6	25.2	26.7	23	49.2	.0759	648	1.54
24	.0201	.024	.028	.032	.000317	24	23.7	25.6	27.6	29.6	31.7	33.6	24	38.6	.0477	818	1.22
25	.0179	.022	.026	.030	.000252	25	29.9	32.3	34.8	37.4	40.0	42.4	25	30.8	.0300	1030	.970
26	.0159	.020	.024	..	.000198	26	37.8	40.8	44.0	47.2	50.5	53.5	26	24.5	.0189	1300	.769
27	.0142	.018	.022	..	.000158	27	47.5	51.4	55.3	59.4	63.6	67.5	27	19.5	.0119	1640	.610
28	.0126	.017	.021	..	.000125	28	60.0	64.7	69.7	75.0	80.2	85.0	28	15.4	.00747	2070	.484
29	.0113	.015	.019	..	.000100	29	75.6	81.7	88.0	94.5	101	107	29	12.2	.00470	2610	.384
30	.0100	.014	.018	..	.0000787	30	95.5	103	112	119	128	136	30	9.71	.00295	3290	.304
31	.00893	.0125	..	..	.0000626	31	120	130	140	151	161	171	31	7.70	.00186	4150	.241
32	.00795	.0115	..	..	.0000496	32	152	164	177	190	203	216	32	6.11	.00117	5230	.191
33	.00708	.0105	..	..	.0000394	33	191	207	223	240	256	272	33	4.84	.000735	6590	.152
34	.00631	.0098	..	..	.0000312	34	242	261	282	302	323	342	34	3.84	.000462	8310	.120
35	.00562	.0086	..	..	.0000248	35	304	328	354	380	407	431	35	3.05	.000291	10500	.0954
36	.00500	.0080	.011	..	.0000196	36	383	414	445	480	513	545	36	2.41	.000183	13200	.0757
37	.00445	.0075	..	..	.0000156	37	484	522	564	605	647	686	37	1.92	.000115	16700	.0600
38	.00397	..	..	..	.0000123	38	610	659	710	762	815	865	38	1.52	.0000721	21000	.0476
39	.00353	..	..	..	.00000979	39	770	830	895	965	1030	1090	39	1.20	.0000455	26500	.0377
40	.00315	..	..	..	.00000776	40	970	1050	1130	1210	1300	1380	40	.955	.0000286	33400	.0299

TABLE XC.—PROPERTIES OF COMMERCIAL COPPER WIRE

Birmingham Wire Gauge (B. W. G.)

Gauge Number.	Diameter (Inches). Bare.	S. C. C.	D. C. C.	T. C. C.	Cross Section. (Sq. In.)	Gauge Number.	Ohms per 1000 Ft. 0 deg. C.	20 deg. C.	40 deg. C.	60 deg. C.	80 deg. C.	100 deg. C.	Gauge Number.	Feet per Ohm at 20 deg. C.	Pounds per Ohm at 20 deg. C.	Feet per Pound.	Pounds per 1000 Ft. (Bare).
0000	.454	..	..	.474	.162	0000	.0464	.0502	.0542	.0583	.0622	.0660	0000	19900	12400	1.60	624
000	.425	..	..	.445	.142	000	.0529	.0573	.0619	.0665	.0710	.0751	000	17500	9540	1.83	547
00	.380	..	..	.400	.113	00	.0663	.0717	.0775	.0833	.0888	.0943	00	14000	6100	2.29	437
0	.340	..	..	.358	.0908	0	.0820	.0896	.0970	.104	.111	.118	0	11200	3910	2.86	350
1	.300	..	..	.318	.0707	1	.107	.115	.124	.133	.1425	.155	1	8690	2370	3.67	272
2	.284	..	.298	.302	.0633	2	.119	.128	.138	.148	.159	.169	2	7790	1900	4.10	244
3	.259	..	.273	.277	.0527	3	.143	.154	.166	.179	.191	.204	3	6480	1320	4.93	203
4	.238	..	.252	.256	.0446	4	.169	.183	.197	.212	.226	.240	4	5470	938	5.83	172
5	.220	..	.234	.238	.0380	5	.198	.214	.231	.248	.265	.282	5	4680	685	6.83	147
6	.203	..	.215	.219	.0324	6	.232	.251	.271	.291	.311	.330	6	3980	497	8.02	125
7	.180	..	.192	.196	.0254	7	.296	.320	.346	.371	.396	.421	7	3130	307	10.2	98.1
8	.165	..	.177	.181	.0214	8	.352	.380	.410	.441	.471	.500	8	2630	217	12.1	82.4
9	.148	..	.160	.164	.0172	9	.437	.473	.511	.549	.585	.621	9	2120	140	15.1	66.3
10	.134	..	.146	.150	.0141	10	.534	.577	.624	.670	.714	.760	10	1730	94.3	18.4	54.4
11	.120	..	.132	.136	.0113	11	.665	.719	.776	.834	.890	.945	11	1390	60.6	22.9	43.6
12	.109	..	.119	.124	.00933	12	.806	.872	.942	1.01	1.08	1.15	12	1150	41.3	27.8	36.0
13	.0950	.101	.105	.109	.00709	13	1.07	1.15	1.24	1.33	1.42	1.53	13	872	23.8	36.6	27.3
14	.0830	.089	.093	.097	.00541	14	1.39	1.50	1.62	1.74	1.86	1.98	14	665	13.9	48.0	20.9
15	.0720	.078	.082	.086	.00407	15	1.85	2.00	2.16	2.32	2.47	2.63	15	501	7.86	63.7	15.7
16	.0650	.071	.075	.079	.00332	16	2.27	2.45	2.64	2.84	3.03	3.23	16	408	5.22	78.2	12.8
17	.0580	.063	.068	.072	.00264	17	2.85	3.08	3.32	3.57	3.81	4.06	17	325	3.31	98.2	10.2
18	.0490	.054	.057	.061	.00189	18	3.99	4.31	4.66	5.00	5.34	5.68	18	232	1.69	138	7.27
19	.0420	.047	.050	.054	.00139	19	5.43	5.87	6.34	6.80	7.27	7.72	19	170	.910	187	5.34
20	.0350	.039	.043	.046	.000961	20	7.80	8.45	9.13	9.80	10.5	11.1	20	118	.439	270	3.71
21	.0320	.036	.040	.044	.000805	21	9.35	10.1	10.9	11.7	12.5	13.5	21	98.9	.307	323	3.10
22	.0280	.032	.036	.040	.000618	22	12.2	13.2	14.2	15.3	16.4	17.4	22	75.5	.180	421	2.37
23	.0250	.029	.033	.037	.000491	23	15.4	16.6	17.9	19.2	20.5	21.9	23	60.0	.114	529	1.89
24	.0220	.026	.030	.034	.000380	24	19.8	21.4	23.1	24.8	26.5	28.2	24	46.8	.068	683	1.47
25	.0200	.024	.028	.032	.000315	25	24.0	25.8	28.0	30.0	32.0	34.0	25	38.6	.0468	826	1.21
26	.0180	.022	.026	.030	.000255	26	29.6	32.0	34.5	37.0	39.6	42.0	26	31.0	.0307	1020	.981
27	.0160	.020	.024	..	.000201	27	37.4	40.5	43.7	47.0	50.1	53.2	27	24.7	.0191	1290	.775
28	.0140	.011	.022	..	.000154	28	48.8	52.8	57.0	61.3	65.4	69.4	28	18.9	.0112	1690	.593
29	.0130	.017	.021	..	.000132	29	56.6	61.3	66.2	71.1	75.9	80.5	29	16.3	.00835	1960	.512
30	.0120	.016	.020	..	.000113	30	66.4	71.9	77.6	83.4	89.0	94.5	30	13.9	.00606	2290	.436
31	.0100	.014	.018	..	.0000787	31	95.5	103	112	119	128	136	31	9.66	.00292	3300	.308
32	.00900	.0125	..	..	.0000636	32	118	128	138	148	158	168	32	7.82	.00192	4080	.245
33	.00800	.0115	..	..	.0000503	33	150	162	175	188	200	214	33	6.18	.00120	5160	.194
34	.00700	.0100	..	..	.0000385	34	195	211	228	245	262	278	34	4.73	.000702	6740	.148
35	.00500	.0080	.011	..	.0000196	35	383	414	446	480	518	545	35	2.41	.000183	13200	.0757
36	.00400	.0070	..	..	.0000126	36	595	645	696	749	801	846	36	1.55	.0000748	20700	.0484

TABLE XCI.—PROPERTIES OF COMMERCIAL COPPER WIRE

STANDARD WIRE GAUGE (S. W. G.)

Gauge Number.	Diameter (Inches).				Cross Section. (Sq. In.)	Gauge Number.	Ohms per 1000 Ft.						Gauge Number.	Feet per Ohm at 20 deg. C.	Pounds per Ohm at 20 deg. C.	Feet per Pound.	Pounds per 100 Ft. (Bare).
	Bare.	S. C. C.	D. C. C.	T. C. C.			0 deg. C.	20 deg. C.	40 deg. C.	60 deg. C.	80 deg. C.	100 deg. C.					
7/0	.500	..	..	.520	.196	7/0	.0383	.0414	.0446	.0480	.0515	.0545	7/0	24200	18300	1.32	756
6/0	.464	..	..	.484	.169	6/0	.0445	.0480	.0518	.0556	.0597	.0631	6/0	20900	13600	1.54	651
5/0	.432	..	..	.452	.147	5/0	.0512	.0553	.0597	.0641	.0687	.0728	5/0	18100	10200	1.77	564
4/0	.400	..	..	.420	.126	4/0	.0597	.0645	.0696	.0747	.0802	.0850	4/0	15500	7500	2.07	484
000	.372	..	..	.392	.109	000	.0690	.0746	.0805	.0865	.0929	.0983	000	13400	5600	2.39	419
00	.348	..	..	.366	.0951	00	.0789	.0852	.0920	.0988	.106	.112	00	11800	4300	2.73	366
0	.324	..	..	.342	.0824	0	.0910	.0984	.106	.114	.122	.130	0	10200	3220	3.15	318
1	.300	..	..	.318	.0707	1	.107	.115	.124	.133	.125	.1515	1	8730	2390	3.67	272
2	.276	..	.290	.294	.0598	2	.126	.136	.147	.157	.169	.179	2	7370	1700	4.34	230
3	.252	..	.266	.270	.0499	3	.151	.163	.176	.189	.202	.214	3	6150	1180	5.20	192
4	.232	..	.246	.250	.0423	4	.178	.192	.207	.222	.238	.252	4	5210	849	6.14	163
5	.212	..	.224	.230	.0353	5	.213	.230	.245	.266	.286	.302	5	4350	592	7.35	136
6	.192	..	.204	.208	.0290	6	.260	.280	.302	.324	.348	.368	6	3580	398	8.97	112
7	.176	..	.188	.192	.0243	7	.310	.334	.360	.387	.415	.440	7	3000	280	10.7	93.7
8	.160	..	.172	.176	.0201	8	.374	.404	.435	.468	.502	.532	8	2480	192	12.9	77.4
9	.144	..	.156	.160	.0163	9	.460	.497	.535	.576	.617	.655	9	2020	127	15.9	62.7
10	.128	..	.140	.144	.0129	10	.582	.628	.677	.728	.780	.828	10	1590	78.5	20.2	49.6
11	.116	..	.126	.131	.0106	11	.710	.766	.827	.888	.954	1.01	11	1300	53.0	24.6	40.7
12	.104	..	.114	.119	.00849	12	.885	.956	1.03	1.11	1.19	1.26	12	1050	34.2	30.6	32.7
13	.0920	.098	.102	.106	.00665	13	1.13	1.22	1.31	1.41	1.51	1.60	13	820	21.0	39.1	25.6
14	.0800	.086	.091	.094	.00508	14	1.50	1.62	1.75	1.87	2.00	2.13	14	621	12.1	51.6	19.4
15	0720	.078	.082	.086	.00407	15	1.85	2.00	2.16	2.32	2.47	2.63	15	508	7.90	63.8	15.7
16	.0641	.070	.075	.078	.00323	16	2.34	2.52	2.72	2.92	3.13	3.32	16	397	4.91	80.7	12.4
17	.0560	.061	.066	.070	.00246	17	3.06	3.30	3.56	3.82	4.10	4.35	17	304	2.88	105	9.49
18	.0480	.053	.056	.060	.00181	18	4.15	4.49	4.84	5.20	5.58	5.91	18	224	1.56	143	6.97
19	.0400	.045	.048	.052	.00126	19	5.97	6.45	6.96	7.47	8.01	8.50	19	155	.750	207	4.84
20	.0360	.040	.044	.048	.00102	20	7.37	7.96	8.60	9.23	9.90	10.5	20	126	.491	258	3.92
21	.0320	.036	.040	.044	.000805	21	9.35	10.1	10.9	11.7	12.5	13.3	21	99.0	.307	323	3.10
22	.0280	.032	.036	.040	.000618	22	12.2	13.2	14.2	15.3	16.4	17.3	22	75.8	.180	422	2.37
23	.0240	.028	.032	.036	.000453	23	16.6	17.9	19.3	20.7	22.2	23.5	23	55.5	.0975	570	1.74
24	.0220	.026	.030	.034	.000380	24	19.8	21.4	23.1	24.8	26.6	28.2	24	46.8	.0685	683	1.46
25	.0200	.024	.028	.032	.000315	25	24.0	25.8	28.0	30.0	32.0	34.0	25	38.6	.0468	826	1.21
26	.0180	.022	.026	.030	.000255	26	29.6	32.0	34.5	37.0	39.6	42.0	26	31.0	.0308	1020	.980
27	.0164	.020	.024	..	.000211	27	35.6	38.4	41.5	44.5	47.7	50.5	27	26.1	.0212	1230	.814
28	.0148	.019	.023	..	.000172	28	43.6	47.1	50.9	54.6	58.6	62.0	28	21.2	.0141	1510	.663
29	.0136	.018	.022	..	.000145	29	51.7	55.1	60.3	64.8	69.5	73.5	29	17.9	.0100	1790	.560
30	.0124	.017	.021	..	.000121	30	62.1	67.1	72.5	77.8	83.5	88.5	30	14.9	.00684	2150	.465
31	.0116	.016	.020	..	.000106	31	71.0	76.6	82.7	88.8	95.3	101	31	13.0	.00530	2460	.407
32	.0108	.015	.019	..	.0000918	32	82.0	88.5	95.5	103	110	117	32	11.3	.00399	2830	.353
33	.0100	.014	.018	..	.0000787	33	95.5	103	112	119	128	136	33	9.70	.00294	3310	.303
34	.00920	.013	..	..	.0000665	34	113	122	131	141	151	160	34	8.20	.00210	3910	.256
35	.00840	.012	..	..	.0000554	35	135	146	157	169	181	192	35	6.85	.00147	4680	.213
36	.00760	.011	..	..	.0000454	36	166	179	193	207	222	235	36	5.60	.000975	5720	.175
37	.00689	.010	..	..	.0000363	37	207	223	240	258	277	294	37	4.49	.000625	7150	.140
38	.00600	.0095	..	..	.0000283	38	266	287	310	332	356	378	38	3.45	.000379	9180	.109
39	.00520	.0085	.011	..	.0000212	39	355	383	413	444	476	504	39	2.62	.000214	12200	.0818
40	.00480	.0080	..	..	.0000181	40	415	448	483	519	557	590	40	2.24	.000156	14300	.0697
41	.00440	.0075	..	..	.0000152	41	494	533	575	618	663	701	41	1.88	.000110	17100	.0586
42	.00400	.0070	..	..	.0000126	42	497	645	695	747	801	850	42	1.55	.0000750	20700	.0484
43	.00360	..	..	..	.0000102	43	738	796	860	922	990	1050	43	1.25	.0000492	25500	.0392
44	.00320	..	..	..	.00000804	44	935	1010	1090	1170	1250	1330	44	.990	.0000306	32300	.0310
45	.00280	..	..	..	.00000616	45	1220	1320	1420	1530	1640	1740	45	.758	.0000180	42200	.0237
46	.00240	..	..	..	.00000452	46	1660	1790	1930	2070	2200	2360	46	.560	.00000975	57400	.0174
47	.00200	..	..	..	.00000314	47	2390	2580	2780	2984	3200	3400	47	.388	.00000469	82600	.0121
48	.00160	..	..	.	.00000201	48	3740	4040	4350	4680	5020	5310	48	.248	.00000193	126000	.00774
49	.00120	..	..	.	.00000113	49	6640	7170	7740	8310	8920	9450	49	.139	.000000605	230000	.00436
50	.00100	..	..		.000000785	50	9530	10300	11100	11900	12800	13500	50	.0970	.000000293	331000	.00303

TABLE XCII.—PHYSICAL AND ELECTRICAL PROPERTIES OF VARIOUS METALS AND ALLOYS.

The following Table gives some physical and electrical properties of various metals and alloys. In nearly every case the name of the observer is stated. No attempt has been made to reconcile divergent measurements, it being left to the reader to follow whichever guide he prefers. The merit of the Table is that it presents in compact form recent information previously scattered through a large number of publications and technical journals.

—	Specific Resistance at 0 Deg. Cent. (Micro-ohms per Cent. Cube).	Micro ohms per Cubic Inch at 0 Deg. Cent.	Resistance of Wire 1 Ft. Long and .001 In. Dia. Ohms at 0 Deg. Cent.	Per Cent. Increase of Resistanbe per Deg. Cent.	Melting Point. Deg. Cent.	Specific Heat. Mean.	Ultimate Tensile Strength. Pounds per Square Inch.	Specific Gravity.	Weight of 1 Cubic Inch. Pounds.
Aluminum (Neuhausen), 99 per cent. Al. Dewar and Fleming	2.56	1.01	15.4	.423	600	.21	..	2.6	.094
Aluminium (Commercial), 97.5 per cent. Al. Dewar and Fleming..	2.67	1.05	16.0	.435	600	.21	..	2.6	.094
Aluminium (annealed). Matthiesen ..	2.89	1.14	17.4	.139	600	.21	..	2.6	.094
Aluminium, 94 per cent.; copper, 6 per cent. Dewar and Fleming	2.90	1.14	17.4	.381					
Aluminum, 94 per cent; copper; 6 per cent. (annealed) Charpentier	3.11	1.23	18.7	..	..	..	..	2.95	.107
Aluminium, 94 per cent.; copper, 6 per cent. (hard). Charpentier	3.33	1.31	20.0	..	..	..	..	2.95	.107
Aluminium, 94 per cent.; silver, 6 per cent. Dewar and Fleming	4.64	1.83	27.8	.238					
Aluminium Bronze, Cu (90 per cent.); Al (10 per cent.). C. Limb	12.6	4.96	75.5	.106	..	..	..	7.7	.278
Antimony (compressed) Matthiesen ..	35.2	13.9	211	.389	440	.049	..	6.7	.242
Bessemer soft steel, C (.045): Mn (.200); S (.030); Sl (0); P (.040). Hopkinson..	10.5	4.14	63.0	..	..	.117	..	7.8	.282
Bismuth (compressed). Matthiesen ..	130	51.2	780	.354	260	.030	..	9.8	.354
Cadmium (pure). Dewar and Fleming ..	10.0	3.93	60.0	.419	..	..	..	8.60	.310
Chrome Bronze, copper, tin, and chromium. Hospitalier	1.64	.645	9.84	..	..	..	64,000	8.9	.321
Chrome bronze, copper, tin, and chromium	4.71	1.85	28.3	..	..	..	107,000		
Chrome bronze, copper, tin, and chromium. Hospitalier	7.80	3.07	46.8	..	..	..	150,000	8.9	.321
Chrome steel (annealed) C, .687: Mn, .28; S, .02: Sl, .134; P, .043; Cr, 1.195. Hopkinson .. .. :	17.9	7.05	108						
Chrome steel (annealed) C, .532; Mn, .393; S, .02; Sl, .22; P, .04; Cr, .621. Hopkinson	19.4	7.65	117						
Electrolytic copper (annealed). Lagarde	1.54	.605	9.25	.445	1050	.093	..	9.05	.327
Electrolytic copper (annealed). Dewar and Fleming..	1.56	.614	9.35	.428	1050	.093	..	8.91	.322
Copper (annealed). Matthiesen	1.59	.625	9.54	.388	1050	..	..	8.9	.321
Copper, 50 per cent.; silver, 50 per cent. Abbott	1.84	.725	11.1						
Copper, 96 per cent.; silicon, 4 per cent. Abbott	2.11	.830	12.7						
Copper, 88 per cent.; silicon, 12 per cent. Abbott	2.94	1.16	17.7						
Copper, 84 per cent.; manganese, 12 per cent.; Ni, 4 per cent. (manganine). Dewar and Fleming	46.7	18.4	28	.00	..	..	..	8.9	.321
Copper 73 per cent.; manganese, 24 per cent.; nickel, 3 per cent. Feussner and Lindeck..	47.7	18.8	287	.003	..	..	..	8.9	.321
Copper, 80.5 per cent.; manganese, 16.5 per cent.; nickel, 3 per cent. (manganine). Tests by G. E. Co.	49.0	19.3	294	.0	..	..	..	8.9	.321
Copper, 83.4 per cent.; Mn. 15.2 per cent.. Fe, 1.4 per cent. Tests by G. E. Co. ..	50.0	19.7	300	.0	..	..	..	8.9	.321
Copper, 79.5 per cent.; Mn. 19.7 per cent.; Fe,. 8 per cent. Tests by G. E. Co.	65.5	25.8	393	.0					
Manganese steel (annealed), C, 1.298: Mn, 8.74; S, .024; Sl, 094; P, .072. Hopkinson	63.3	24.9	380	..	1260	..	..	7.8	.282
Manganese steel (Hadfield), C, 1.005; Mn, 12.36; S, .038; Sl, 204; P, .070. Hopkinson	65.5	25.8	393	..	1260	..	..	7.8	.282
Manganese steel (Hadfield), 12 per cent. Mn. Dewar and Fleming	67.1	26.4	404	.127	1260	..	..	7.8	.282
Manganese steel (Hadfield's Hecla Foundry), C, 1.001; Mn, 11.40; P, .059. Tests by G. E. Co.	69.0	27.1	414	.135	1260	..	..	7.8	.282
Manganese steel. Hospitalier	75.0	29.5	450	.136	1260	..	230,000	7.8	.282
Copper, 70 per cent.; manganese, 30 per cent. Feussner and Lindeck	101.0	39.8	605	.004					
Mercury. Matthiesen	94.3	37.1	566	.072	..	.032	..	13.6	.490
Nickel. Dewar and Fleming	12.3	4.85	73.7	.62	1500	.109	..	8.9	.321
Nickel (annealed). Matthiesen	12.4	4.89	74.4	.50	1500	.109	..	8.9	.321
Nickel steel (Hadfield), 4.35 per cent.: nickel. Dewar and Fleming	29.5	11.6	177	.201					
Nickeline. Lange and Co., Berlin ..	40.0	15.8	240						
Palladium (pure). Dewar and Fleming..	10.2	4.02	61.1	.354					
Platinum, 67 per cent.; Silver, 33 per cent. (alloy). Matthiesen	24.2	9.54	145	.133					
Platinum, 80 per cent,; Iridium, 20 per cent. Dewar and Fleming	30.9	12.2	186	.082					
Platinoid. Dewar and Fleming	41.7	16.4	251	.031	..	..	..	8.8	.318
Platinoid-martino. Dewar and Fleming	43.6	17.2	262	..	..	..	..	8.8	.318
Platinoid-martino	33.0	13.0	198	.024					

TABLE XCII.—PHYSICAL AND ELECTRICAL PROPERTIES OF VARIOUS METALS AND ALLOYS.—*Continued*

—	Specific Resistance at 0 Deg. Cent. (Micro-ohms per Cent. Cube).	Micro-ohms per Cubic Inch at 0 Deg. Cent.	Resistance of Wire 1 Ft. Long and .101 In. Dia. Ohms at 0 Deg. Cent.	Per Cent. Increase of Resistance per Deg. Cent.	Melting Point. Deg. Cent.	Specific Heat. Mean.	Ultimate Tensile Strength. Pounds per Square Inch.	Specific Gravity.	Weight of 1 Cubic Inch. Pounds.
Copper, 99.29 per cent.; zinc, .71 per cent. R. Haas	1.83	.720	11.0	.373					
Copper, 90.9 per cent.; zinc, 9.1 per cent. R. Haas	3.64	1.43	21.8	.204					
Zinc, 99.5 per cent.; copper, 5 per cent. R. Haas	5.88	2.31	35.3	.385	..	.095	..	7.1	.256
Copper, 65.8 per cent.; zinc, 34.2 per cent. R. Haas	6.30	2.48	37.8	.158					
Cast copper	4.65	2.83	27.9						
Copper, 90 per cent.; lead, 10 per cent. Abbott	5.28	2.08	31.7						
Copper, 97 per cent.; aluminium, 3.0 per cent. Dewar and Fleming	8.84	3.48	53.0	.090					
Copper, 87 per cent.; Ni, 6.5 per cent.; Al, 6.5 per cent. Dewar and Fleming	14.9	5.87	89.5	.0645					
Copper, 90 per cent.; arsenic, 10 per cent. Abbott	17.6	6.94	106						
Copper, 75 per cent.; nickel, 25 per cent. Feussner and Lindeck	34.2	13.5	205	.019					
German silver, Cu (60); Zn (25); Ni (15). Feussner and Lindeck	30.0	11.8	180	.036					
Gold (annealed). Matthiesen	2.04	.803	12.3	.365	1100	.032	..	19.3	.695
Gold, 99.9 per cent. (pure). Dewar and Fleming	2.20	.865	13.2	.377	1200	.032	..	19.3	.695
Gold, 90 per cent.; silver, 10 per cent. Dewar and Fleming	6.28	2.47	37.7	.124					
Gold, 67 per cent.; silver, 33 per cent. (alloy). Matthiesen	10.8	4.25	64.8	.065					
Iron (very pure). Dewar and Fleming	9.07	3.57	54.5	.625	..	.113	..	7.8	.282
Iron, with .25 per cent. Mn and 0.1 per cent. S. Dewar and Fleming	10.5	4.14	63.0	.544	..	.113	..	7.8	.282
White cast iron. C, 2.04; graphite, O, Mn, .386; S, .467; Sl, .764; P, .458. Hopkinson	56.6	22.3	340	..	1130	..	..	7.20	.260
Spiegeleisen—C, 4.5 per cent.; Mn, 7.97 per cent., S traces, Sl, .502 per cent.; P, .128 per cent. Hopkinson	105	41.4	630						
Grey cast iron—C, 3.46; graphite, 2.06; Mn, .173; S, .042; Sl, 2.04; P, .151. Hopkinson	114	44.9	684	..	1220	..	..	7.20	.260
Wrought iron (annealed). Hopkinson	13.8	5.44	82.8	..	..	..	..	7.8	.282
Lead (compressed). Matthiesen	19.5	7.68	117	.387	330	.032	..	11.4	.410
Lead (pure). Dewar and Fleming	20.4	8.04	123	.411	330	.032	..	11.4	.410
Magnesium. Dewar and Fleming	4.36	1.72	26.2	.381	..	.25	..	1.74	.063
Manganese steel (annealed), C, .674; Mn, 4.73; S, .023; Sl, .608; P, .078. Hopkinson	39.3	15.5	236	..	1260	..	..	7.8	.282

—	Specific Resistance at 0 Deg. Cent. (Micro-ohms per Cent. Cube).	Micro-ohms per Cubic Inch at 0 Deg. Cent.	Resistance of Wire 1 Ft. Long and .001 In. Dia. Ohms at 0 Deg. Cent.	Per Cent. Increase of Resistance per Deg. Cent.	Melting Point. Deg. Cent.	Specific Heat. Mean.	Ultimate Tensile Strength. Pounds per Square Inch.	Specific Gravity.	Weight of 1 Cubic Inch. Pounds.
Platinum (soft annealed, pure)	8.25	3.24	49.5	..	1775	.032	..	21.2	.765
Platinum (annealed). Matthiesen	8.98	3.53	53.9	.247	1775	.032	..	21.2	.765
Platinum (pure) wire, .0259 cm. in diam. Dewar and Fleming	11.0	4.34	66.0	.35	1775	.032	..	21.2	.765
Platinum, 90 per cent.; Rodium, 10 per cent. Dewar and Fleming	21.1	8.30	127	.143					
Platinum, 90 per cent.; Iridium, 10 per cent. (alloy). Matthiesen	21.6	8.50	130	.133					
Phosphor-bronze, with 9 per cent. phosphorus. Abbott	32.5	12.8	195						
Phosphor-bronze (copper, tin, and phosphorus). Hospitalier	1.6	.630	9.6	.394	..	..	64,000	8.9	.321
Phosphor-bronze (copper, tin, and phosphorus). Hospitalier	5.6	2.20	33.6	.394	..	..	117,000	8.9	.351
Phosphor-bronze, with 10 per cent. of tin. Abbott	24.6	9.69	148						
Pure electrolytic (annealed) silver. Dewar and Fleming	1.47	.579	8.82	.400	950	.056	..	10.5	.379
Silver (annealed). Matthiesen	1.49	.586	8.94	.377	950	.056	..	10.5	.379
Silverine, Cu (77), Ni (17), Fe (2), Zn (2), CO (2). Dewar and Fleming	2.06	.810	12.4	.285					
Silver, 80 per cent.; palladium, 20 per cent. Dewar and Fleming	15.0	5.90	90.0						
Silver, 66 per cent.; platinum, 33 per cent. Dewar and Fleming	31.6	12.4	190	.0243					
Silicon-bronze (copper, tin, and silicon). Hospitalier	1.67	.657	10.0	.152	..	..	64,000	8.9	.321
Silicon-bronze (copper, tin, and silicon). Hospitalier	2.69	1.06	16.2	..	..	..	93,000	8.9	.321
Silicon-bronze (copper, tin, and silicon). Hospitalier	5.76	2.27	34.6	..	..	..	107,000	8.9	.321
Silicon-bronze (copper, tin, and silicon). Hospitalier	7.80	3.07	46.8	..	..	..	143,000	8.9	.321
Silicon-steel (annealed) C, .685; Mn, .694; S, .024; Sl, 3.44; P, .133. Hopkinson	61.9	24.3	372						
Thallium (pure). Dewar and Fleming	17.6	6.94	106	.398					
Tin (pure). Dewar and Fleming	13.1	5.16	78.5	.440	230	.056	..	7.3	.264
Tin (compressed). Matthiesen	13.1	5.16	78.5	.365	230	.056	..	7.3	.264
Tungsten steel (annealed) C, 1.36; Mn, .36; S, 0; Sl, .043; P, .047; tungsten, 4.65. Hopkinson	22.5	8.86	135						
Whitworth soft steel (annealed) C, .090; Mn, 153; S, .016; Sl, .0; P, .042. Hopkinson	10.8	4.25	64.8	..	..	.117	..	7.8	.282
Zinc (very pure). Dewar and Fleming	5.75	2.26	34.5	.406	415	.095	..	7.1	.256
Zinc (compressed). Matthiesen	5.80	2.28	34.8	.365	415	.095	..	7.1	.256

ERRATA.

FOLDING TABLE.—PROPERTIES OF COPPER WIRES, &c.

The wire B. & S. 29 is given as of diameter 0.3 mm., or 0.0118 in.; but the true diameter of B. & S. 29 is 0.0113 in.; the figures in this line therefore refer only to a wire of 0.0118 in. (0.3 mm.) diameter and not to B. & S. 29.

S. W. G. 40, diameter S. C. C., should read 0.0080 in., instead of 0.0090 in.

S DIFFERENT COUNTRIES.

80 Cent.		Gauge Stand.	Gauge Number.	Metres per Ohm at 20 deg. Cent.	Feet per Ohm at 20 deg. Cent.	Kilograms per Ohm at 20 deg. Cent.	Pounds per Ohm at 20 deg. Cent.	Metres per Kilogram.	Feet per Pound.	Kilograms per Kilometre (Bare).	Pounds per 1000 Ft. (Bare).
Km.	0 Ft.										
.1690	0545	S W G	7/0	7380	24200	8300	18300	.89	1.32	1126	756
.19	0614	..	..	6550	21400	6600	14600	.995	1.48	1010	680
.1960	631	S W G	6/0	6370	20900	6170	13600	1.04	1.54	970	651
.1980	643	B & S	0000	6215	20400	5940	13100	1.05	1.56	955	641
.2050	660	B W G	0000	6065	19900	5620	12400	1.08	1.60	930	624
.226	28	S W G	5/0	5500	18100	4620	10200	1.19	1.77	840	564
.2330	51	B W G	000	5320	17500	4330	9540	1.23	1.83	815	547
.2500	12	B & S	000	4950	16200	3740	8230	1.32	1.97	758	508
.2650	50	S W G	4/0	4720	15500	3400	7500	1.39	2.07	720	484
.273	85	..	..	4550	14900	3180	7030	1.425	2.12	701	471
.2900	43	B W G	00	4260	14000	2760	6100	1.54	2.29	650	437
.3050	83	S W G	000	4100	13400	2540	5600	1.61	2.39	622	419
.3150	2	B & S	00	3950	12900	2350	5180	1.67	2.48	600	403
.337	9	..	..	3690	12100	2090	4625	1.76	2.61	567	382
.3500	.2	S W G	00	3600	11800	1950	4300	1.84	2.73	545	366
.3600	.8	B W G	0	3400	11200	1780	3910	1.92	2.86	522	350
.4000	29	B & S	0	3100	10200	1480	3260	2.10	3.13	477	320
.4000	30	S W G	0	3100	10200	1460	3220	2.12	3.15	475	318
.429	385	..	..	2910	9550	1300	2870	2.23	3.31	448	302
.4675	515	S W G	1	2660	8730	1080	2380	2.47	3.67	405	272
.4675	515	B W G	1	2650	8690	1075	2370	2.47	3.67	405	272
.500	62	B & S	1	2450	8080	930	2050	2.65	3.95	376	253
.520	69	B W G	2	2370	7790	860	1900	2.75	4.10	364	244
.55	79	S W G	2	2245	7370	770	1700	2.92	4.34	342	230
.63	04	B W G	3	1970	6480	600	1320	3.30	4.93	302	203
.63	04	B & S	2	1900	6410	585	1290	3.35	4.98	300	201
.66	214	S W G	3	1870	6150	535	1180	3.50	5.20	285	192
.74	240	B W G	4	1660	5470	425	938	3.92	5.83	256	172
.7	245	..	..	1640	5390	414	915	3.97	5.90	252	169
.7	252	S W G	4	1590	5210	385	849	4.12	6.14	248	163
.8	258	B & S	3	1540	5080	367	810	4.20	6.28	237	159
.	282	B W G	5	1420	4680	310	685	4.60	6.83	219	147
.	302	S W G	5	1320	4350	269	592	4.95	7.35	202	136
1.	325	B & S	4	1230	4030	230	509	5.31	7.91	188	126
1.	330	B W G	6	1210	3980	225	497	5.40	8.02	186	125
1.	351	..	..	1140	3750	200	440	5.69	8.48	175.5	118
1.	368	S W G	6	1090	3580	180	398	6.00	8.97	167	112
1	410	B & S	5	975	3200	146	320	6.70	9.98	149	100
1	21	B W G	7	950	3130	140	307	6.85	10.2	146	98.1
	40	S W G	7	915	3000	127	280	7.20	10.7	140	93.7
	0	B W G	8	800	2630	98	217	8.10	12.1	123	82.4
	6	B & S	6	775	2540	91	202	8.45	12.6	118	79.5
		S W G	8	760	2480	87	192	8.70	12.9	116	77.4
		..	..	730	2390	81.9	180	8.9	13.2	112	75.7
		B W G	9	645	2120	63	140	10.15	15.1	99	66.3
		B & S	7	610	2010	57.5	127	10.70	15.9	94	63.0
		S W G	9	615	2020	57.5	127	10.70	15.9	93.5	62.7
		B W G	10	525	1730	42.6	94.3	12.40	18.4	81.2	54.4
		B & S	8	490	1600	36.0	79.7	13.40	20.0	74.5	50.0
		S W G	10	485	1590	35.5	78.5	13.60	20.2	74.00	49.6
		B W G	11	425	1390	27.5	60.6	15.40	22.9	65.00	43.6
		..	..	410	1342	25.9	57.0	15.8	23.5	63.2	42.5
	5	S W G	11	395	1300	24	53.0	16.50	24.6	60.80	40.7
1.	20	B & S	9	385	1270	22.7	50.1	16.90	25.2	59.00	39.6
1.	55	B W G	12	350	1150	18.8	41.3	18.70	27.8	53.8	36.0
1.	.90	S W G	12	320	1050	15.5	34.2	20.50	30.6	48.7	32.7
1.	.10	B & S	10	305	1000	14.2	31.5	21.40	31.8	46.9	31.4
1.	4.65	B W G	13	265	872	10.8	23.8	24.50	36.6	40.5	27.3
1	4.95	W G	13	250	820	9.5	21.0	26.2	39.1	38.00	25.6
1	5.10	& S	11	240	795	9.0	19.8	27.00	40.1	37.00	24.9
2.	6.10	W G	14	203	665	6.3	13.9	32.20	48.0	31.20	20.9
	6.40	& S	12	192	631	5.68	12.5	34.30	50.6	29.50	19.8
2.	6.55	W G	14	189	621	5.50	12.1	34.60	51.6	29.00	19.4
2.	6.80	..	..	182.5	599	5.11	11.2	35.5	53.0	28.2	18.85
2.	8.10		15	152	501	3.55	7.86	42.50	63.7	23.40	15.7
2.	8.10	G	15	153	503	3.59	7.90	42.70	63.8	23.40	15.7
3.	8.10	G	13	152	500	3.55	7.84	42.70	63.8	23.40	15.7
3.	10.00	S	16	124	408	2.36	5.22	52.50	78.2	19.10	12.8
3.	10.20	G	14	120	397	2.23	4.93	54.00	80.4	18.50	12.4
3	10.20		16	120	397	2.23	4.91	54.20	80.7	18.50	12.4
3.	12.50		17	99	325	1.50	3.31	66.00	98.2	15.20	10.2
4.	13.00		15	96	315	1.40	3.10	68.00	101	14.70	9.86
4.	13.40		17	92	304	1.30	2.88	70.50	105	14.15	9.49
5.	16.20		16	78	249	.885	1.95	86.00	128	11.80	7.82
5.	17.60		18	71	232	.767	1.69	92.70	138	10.80	7.27
6.	18.30		18	68.2	224	.707	1.56	96.10	148	10.39	6.97
7.	20.6		17	60.4	198	.558	1.23	108	161	9.23	6.20
7.	23.8		19	51.8	170	.413	.910	126	187	7.95	5.34
8.	25.9		18	47.8	157	.350	.772	136	203	7.38	4.92
	26.8		19	47.3	155	.340	.750	139	207	7.20	4.84

FFERENT COUNTRIES—*Continued.*

ent) deg. Cent.		Gauge Stand.	Gauge Number.	Metres per Ohm at 20 deg. Cent.	Feet per Ohm at 20 deg. Cent.	Kilograms per Ohm at 20 deg. Cent.	Pounds per Ohm at 20 deg. Cent.	Metres per Kilogram.	Feet per Pound.	Kilograms per Kilometre (Bare).	Pounds per 1000 Ft. (Bare).
100m.	1000 Ft.										
9.0	8.85	..	..	45.5	149	.320	.705	142	212	7.0	4.78
9.48	10.5	S W G	20	38.4	126	.222	.491	171	258	5.84	3.92
9.8	10.6	B & S	19	37.8	124	.220	.485	173	257	5.81	3.90
10.7	10.9	..	..	37.0	121	.210	.460	176	263	5.6	3.79
10.4	11.1	B W G	20	36.0	118	.199	.439	182	270	5.52	3.71
12.80	13.3	S W G	21	30.2	99.0	.139	.307	217	323	4.62	3.10
12.8	13.5	B W G	21	30.2	98.9	.139	.307	217	323	4.62	3.10
12.6	13.4	B & S	20	30.2	98.7	.138	.305	217	323	4.62	3.10
13.2	13.8	..	..	29.1	95.0	.130	.285	223	332	4.48	3.0
15.8	16.8	B & S	21	23.7	77.5	.0870	.192	274	408	3.65	2.45
16.4	17.4	B W G	22	23.0	75.5	.0816	.180	283	421	3.53	2.37
16.4	17.3	S W G	22	23.0	75.8	.0816	.180	284	422	3.53	2.37
17.0	17.8	..	..	22.5	73.5	.077	.169	290	434	3.42	2.3
20.0	21.2	B & S	22	18.9	62.1	.0648	.121	346	514	2.90	1.95
20.5	21.9	B W G	23	18.4	60.0	.0516	.114	356	529	2.82	1.89
22.2	23.5	S W G	23	17.0	55.5	.0442	.0975	386	570	2.59	1.74
23.2	24.5	..	..	16.4	53.5	.041	.090	398	593	2.5	1.68
25.2	26.7	B & S	23	15.0	49.2	.0348	.0759	435	648	2.29	1.54
26.5	28.2	B W G	24	14.2	46.8	.0308	.068	460	683	2.19	1.47
26.6	28.2	S W G	24	14.2	46.8	.0308	.0685	460	683	2.18	1.46
31.7	33.6	B & S	24	11.8	38.6	.0216	.0477	555	818	1.82	1.22
32.0	34.0	B W G	25	11.8	38.6	.0216	.0468	555	826	1.80	1.21
32.0	34.0	S W G	25	11.8	38.6	.0216	.0468	555	826	1.80	1.21
33.2	35.5	..	..	11.4	37.2	.0198	.0435	580	850	1.74	1.17
39.6	42.0	B W G	26	9.5	31.0	.0139	.0307	686	1020	1.46	.981
39.6	42.0	S W G	26	9.5	31.0	.0139	.0308	686	1020	1.46	.980
40.0	42.0	B & S	25	9.45	30.8	.0136	.0300	698	1030	1.45	.97
47.7	50.5	S W G	27	7.95	26.1	.00960	.0212	827	1230	1.21	.814
50.1	53.2	B W G	27	7.53	24.7	.00865	.0191	868	1290	1.15	.775
50.5	53.5	B & S	26	7.46	24.5	.00857	.0189	875	1300	1.14	.769
52.2	55.4	..	..	7.3	24	.00815	.0178	894	1350	1.12	.740
58.6	62.0	S W G	28	6.46	21.2	.00639	.0141	1015	1510	.986	.663
63.6	67.5	B & S	27	5.94	19.5	.00539	.0119	1100	1640	.908	.610
65.4	69.4	B W G	28	5.76	18.9	.00508	.0112	1135	1690	.882	.593
69.5	73.5	S W G	29	5.46	17.9	.00454	.0100	1203	1790	.834	.560
75.9	80.5	B W G	29	4.97	16.3	.00378	.00835	1319	1960	.762	.512
80.2	85.0	B & S	28	4.69	15.4	.00337	.00747	1390	2070	.720	.484
83.5	88.5	S W G	30	4.54	14.9	.00314	.00684	1444	2150	.692	.465
89.0	94.5	B W G	30	4.24	13.9	.00275	.00606	1540	2290	.650	.436
93	98	B & S	29	4.1	13.4	.00258	.00570	1580	2360	.625	.41
95.3	101	S W G	31	3.96	13.0	.00240	.00530	1653	2460	.606	.407
110	117	S W G	32	3.45	11.3	.00181	.00399	1900	2830	.525	.353
128	136	B & S	30	2.96	9.71	.00134	.00295	2210	3290	.452	.304
128	136	B W G	31	2.95	9.66	.00132	.00292	2218	3300	.445	.303
128	136	S W G	33	2.96	9.70	.00133	.00294	2224	3310	.451	.303
151	160	S W G	34	2.50	8.20	.000952	.00210	2628	3910	.381	.256
158	168	B W G	32	2.36	7.82	.000870	.00192	2741	4080	.365	.245
161	171	B & S	31	2.34	7.70	.000844	.00186	2790	4150	.359	.241
181	192	S W G	35	2.09	6.85	.000666	.00147	3145	4680	.318	.213
200	214	B W G	33	1.89	6.18	.000544	.00120	3470	5160	.289	.194
203	216	B & S	32	1.86	6.11	.000530	.00117	3515	5230	.284	.191
207	220	..	..	1.82	6.0	.000505	.00111	3600	5400	.277	.185
222	235	S W G	36	1.71	5.60	.000442	.000975	3840	5720	.261	.175
256	272	B & S	33	1.48	4.84	.000333	.000735	4430	6590	.226	.152
262	278	B W G	34	1.44	4.73	.000318	.000702	4525	6740	.220	.148
277	294	S W G	37	1.37	4.49	.000283	.000625	4820	7150	.208	.140
323	342	B & S	34	1.17	3.84	.000210	.000462	5580	8310	.179	.120
356	378	S W G	38	1.05	3.45	.000172	.000379	6170	9180	.162	.109
407	431	B & S	35	.930	3.05	.000132	.000291	7060	10500	.142	.0954
476	504	S W G	39	.798	2.62	.0000970	.000214	8200	12200	.122	.0818
513	545	B & S	36	.735	2.41	.0000830	.000183	8875	13200	.113	.0757
513	545	B W G	35	.735	2.41	.0000830	.000183	8875	13200	.113	.0757
557	590	S W G	40	.683	2.24	.0000707	.000156	9610	14300	.104	.0697
647	686	B & S	37	.585	1.92	.0000522	.000115	10220	16700	.0894	.0600
663	701	S W G	41	.574	1.88	.0000499	.000110	11500	17100	.0874	.0586
801	846	B W G	36	.472	1.55	.0000339	.0000748	13900	20700	.0720	.0484
801	850	S W G	42	.472	1.55	.0000340	.0000750	13900	20700	.0720	.0484
815	865	B & S	38	.463	1.52	.0000327	.0000721	14120	21000	.0709	.0476
832	885	..	..	.455	1.49	.000032	.0000705	14200	21200	.07	.0473
990	1050	S W G	43	.382	1.25	.0000223	.0000492	17130	25500	.0584	.0392
1030	1090	B & S	39	.366	1.20	.0000206	.0000455	17800	26500	.0561	.0377
1250	1330	S W G	44	.302	.990	.0000139	.0000306	21700	32300	.0462	.0310
1300	1380	B & S	40	.291	.955	.0000130	.0000286	22440	33400	.0445	.0299
1640	1740	S W G	45	.231	.758	.00000816	.0000180	28400	42200	.0353	.0237
2200	2360	S W G	46	.171	.560	.00000442	.00000975	38600	57400	.0259	.0174
3200	3400	S W G	47	.118	.388	.00000213	.00000469	55500	82600	.0180	.0121
5020	5310	S W G	48	.0756	.248	.000000875	.00000193	86750	126000	.0115	.00774
8920	9450	S W G	49	.0424	.139	.000000274	.000000605	154800	230000	.00550	.00436
12800	13500	S W G	50	.0296	.0970	.000000133	.000000293	218500	331000	.00451	.00303

INDEX

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